OBBOTEC-SPEX carbon footprint assessment

Screening life cycle assessment of selective plastic extraction (SPEX)

CE Delft

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Content

Summary

SPEX Technology is a subsidiary company of OBBOTEC, developing a recycling technology called Selective Plastic EXtraction, or SPEX in short. The goal of this screening life cycle assessment (LCA) is to estimate the carbon footprint of recycling three different waste streams with the SPEX process and compare the results to reference plastic production/waste treatment processes.

While this (ex-ante) assessment contains various uncertainties, SPEX recycling is estimated to offer substantial carbon footprint reductions compared to reference processes for all waste streams studied.

Life cycle assessment method

The screening LCA estimates the carbon footprint of SPEX recycling and compares it to fossil production processes (product perspective) and current waste treatments (waste perspective). As no SPEX plant has been built at the 20 kt/yr scale studied here, the (ex-ante) assessment is based on the mass- and energy balances from the conceptual design study of SPEX for the process at full scale and lab tests and pilot tests on smaller 1 kt/yr pilot scale at their location at Plant One Rotterdam. This data is combined with literature data and assumptions for background processes.

Three distinct waste streams are studied as feedstock for SPEX:
1. HDPE from mixed post-consumer waste.
2. Laminate packaging (PP/PET/aluminium) from mixed post-consumer waste.
3. Medical breathing tubes (PP/LDPE/copper).

Product and waste perspective

The SPEX technology has two functions: treatment of plastic waste and production of new plastics. Therefore, the carbon footprint of the technology is analysed from two perspectives: the waste perspective and the product perspective.

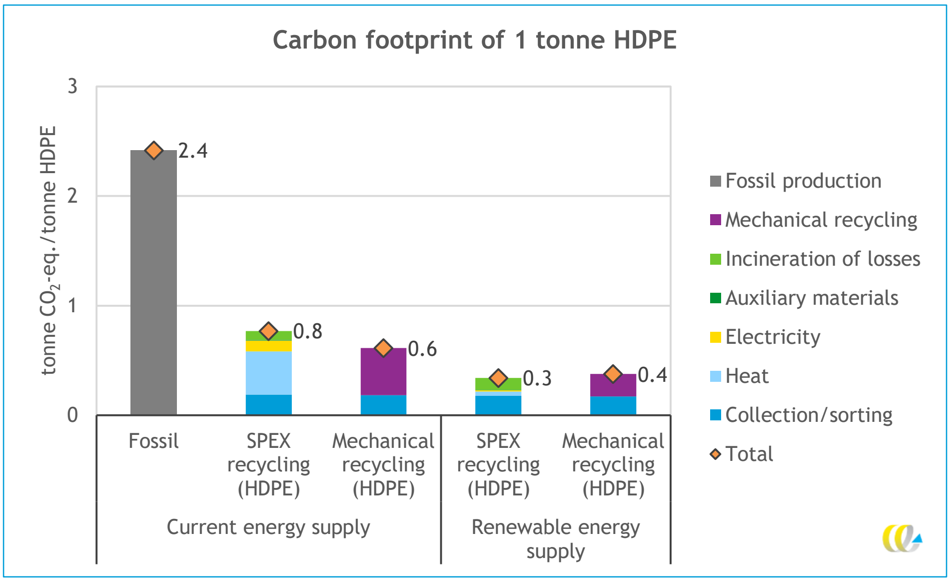
In the **waste perspective**, the treatment of plastic waste streams by SPEX is compared to conventional waste treatment technologies (incineration, mechanical recycling). This perspective is relevant for policymakers interested in comparing the environmental implications of treating waste in different installations. To account for the different products (plastics or energy) of these processes, a substitution approach is applied.

In the **product perspective,** the production of plastics by SPEX is compared to conventional plastic production (from fossil feedstock or by mechanical recycling). This can be used in business-to-business communication with parties interested in sourcing recycled plastics produced by SPEX. A credit for avoided waste incineration is not included.

Detailed results: HDPE from mixed post-consumer waste

Figure 1 shows the product perspective results for the first waste stream, HDPE from mixed post-consumer waste. It compares the carbon footprint of 1 tonne of HDPE produced by SPEX, mechanical recycling and from fossil resources (newest ecoinvent data). The left three bars show the results when using the current average energy supply. The right three bars show the results when a renewable energy mix is used for SPEX recycling and mechanical recycling.

Figure 1 - Carbon footprint of HDPE production (cradle-to-gate) - recycling of HDPE waste



The carbon footprint of HDPE produced via SPEX is substantially lower (a reduction of 1.6 t CO_2-eq./t) than the carbon footprint of fossil HDPE. The carbon footprint reduction is increased further (2.1 t CO_2-eq./t) with a renewable energy mix. Compared to mechanically recycled HDPE, the carbon footprint of HDPE from SPEX recycling is estimated to be slightly higher with the current energy supply. When using renewable energy, the carbon footprints are comparable.

With the current energy supply, the carbon footprint of the SPEX technology stems primarily from the use of heat and the collection and sorting processes. The use of electricity and the incineration of losses make up the rest of the carbon footprint.

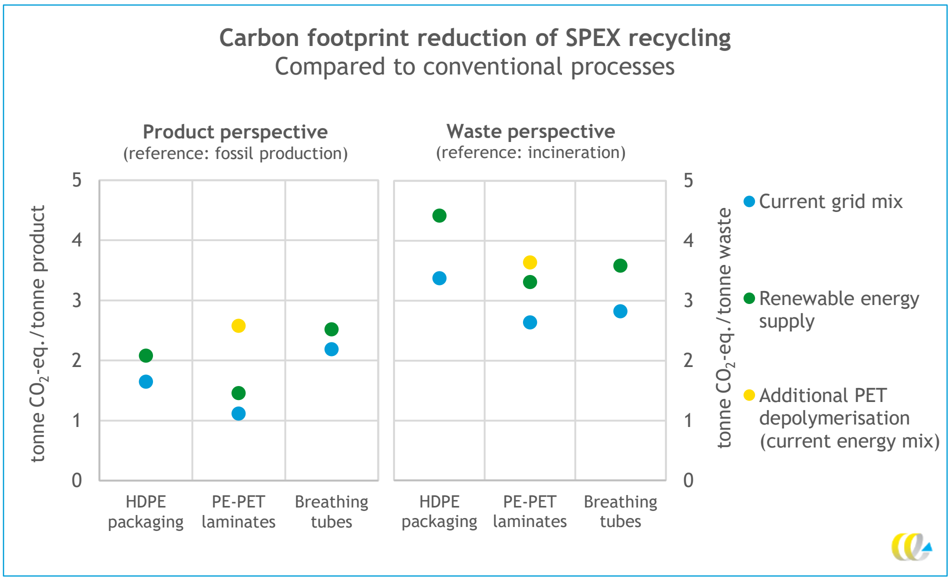
Detailed results for the other feedstocks as well as the waste perspective are available in the full report.

Overview of all carbon footprint results

In Figure 2, the carbon footprint results for all studied cases are summarized. The figure shows the carbon footprint reduction achieved by SPEX recycling compared to fossil production or incineration.

Note that in this graph, higher values represent larger carbon footprint reductions.

Figure 2 - Overview of estimated carbon footprint reductions of SPEX recycling, per tonne output (product perspective) or per tonne waste input (waste perspective)



The left side of Figure 1 shows product perspective results. The analysis shows that SPEX recycling offers a substantially lower (1.1 to 1.9 t CO_2-eq./t) estimated carbon footprint than fossil production of polyolefins (product perspective analyses, current energy mix). This reduction is increased further to 1.5 to 2.2 t CO_2-eq./t when assuming renewable energy supply for SPEX.

The reduction is largest when treating medical breathing tubes, which can be fully recycled with SPEX dissolution (closed-loop recycling). In contrast, the reduction is smallest for packaging laminates, where PET and additives are lost to incineration. However, if the PET waste (28%wt. of the feedstock) can be recovered by combining SPEX with a PET depolymerisation plant, the carbon footprint reduction increases substantially.

The right side shows the waste perspective results. Here, the estimated carbon footprint reductions achieved by SPEX follow the same trends. However, the reductions are higher, as these results also include a credit for avoided fossil production of the recovered materials (see discussion below). The waste perspective reductions range from 2.6 to 3.4 t CO_2-eq./t waste treated when using the current energy mix, and 3.3 to 4.5 t CO_2-eq./t waste treated when using renewable energy for SPEX dissolution. These reductions are comparable to those achieved by mechanical recycling.

Uncertainties and recommendations

The screening LCA contains some important assumptions and other limitations. These can be addressed in future updates to increase the robustness of the conclusions presented here. Key limitations are:

- The analysis is primarily based on SPEX process data projected for 20 kt/yr operation. Once in operation, it is important to validate this data (energy consumption, solvent recovery rates, mass balances, etc.) in full-scale practice.
- The first product perspective analysis compares SPEX, mechanical recycling and fossil production routes of 1 tonne PE. However, the quality/purity of the products may not be fully identical and there can be regulatory limitations affecting whether a specific

product can be used in specific applications (e.g. food contact). While the outputs of all three systems are likely interchangeable in many applications, it is relevant to consider quality differences in greater detail when analysing specific product applications.

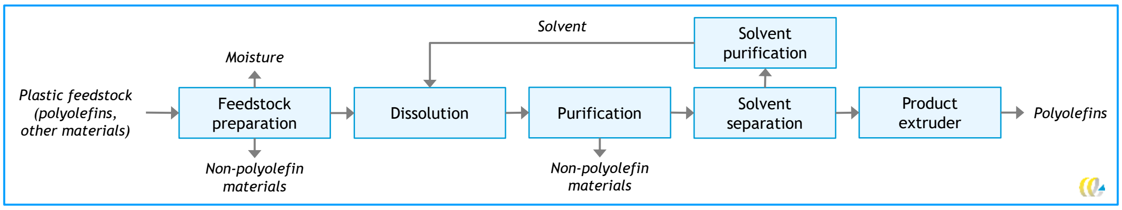
- The screening LCA contains various assumptions and use of background data, which can be improved in future updates.
- This screening study focuses on the carbon footprint performance of different technologies. Additional environmental indicators can be included in a more extensive LCA.

1 Introduction

OBBOTEC is developing a plastic recycling technology based on selective dissolution, called SPEX. The goal of this screening life cycle assessment (LCA) is to estimate the carbon footprint of recycling three different waste streams with the SPEX process and compare the results to alternative plastic production/waste treatment processes.

The Selective Plastic EXtraction (SPEX) process is illustrated in Figure 3. SPEX enables the recovery of polyolefin plastics (PE and PP) from mixed waste streams by physically dissolving these plastics. Other plastics, additives and contaminants are not dissolved and are removed. The solvent used during dissolution is recovered and reused.

Figure 3 - Flow diagram of SPEX dissolution recycling



This carbon footprint assessment is considered a *screening* LCA, as the aim is to provide a first indication of how the SPEX process compares to alternative processes when treating different feedstocks. As no SPEX plant has been built at the 20 kt/yr scale studied here, the (ex-ante) assessment is based on models/projections of the process at full scale and results from the test facilities at Plant One Rotterdam.

Three distinct waste streams that can be used as feedstock for SPEX are studied:
1. HDPE from mixed post-consumer waste.
2. Laminate packaging (PP/PET/aluminium) from mixed post-consumer waste.
3. Breathing tubes (PP/LDPE/copper).

All three are studied from both a product perspective and a waste perspective (see also Chapter 2), enabling comparisons to both fossil plastic production processes and waste treatment processes such as incineration and mechanical recycling.

The rest of this report is structured as follows:
— Chapter 2 covers the methodology applied by discussing the LCA's goal and scope.
— Chapter 3 discusses the LCA modelling/life cycle inventory.
— Chapter 4 presents the carbon footprint results for the three waste feedstocks.
— Chapter 5 summarizes the conclusions and discusses key uncertainties/limitations.

In Annex A, the LCA methodology is further explained.

Motivation to conduct screening LCA study
SPEX Technology has provided the following background/motivation for commissioning this LCA project:
'OBBOTEC's Selective Plastic EXtraction (SPEX) offers an innovative plastic-to-plastic recycling solution for all PE and PP waste streams. The unique (National Research Council et al.) dissolution process has several benefits:

1. High product quality, which cannot be achieved through mechanical recycling.
2. High product yields (exceeding 95%), which cannot be achieved with chemical recycling (pyrolysis, gasification).
3. Low energy use, due to mild process conditions.

SPEX has successfully conducted various tests in laboratory and pilot units. These have proven that the technology can be applied to real-life (2D and 3D) waste streams that are difficult to handle with conventional mechanical recycling, including mixed plastics, multilayers, laminates and flexible materials.

SPEX Technology can offer very high quality outputs as plastic grains are fully dissolved, enabling the process to remove contaminants at a molecular level. Unlike mechanical recycling, for example, the dissolution process removes colourants and odorants, resulting in transparent and odor-free recycled plastics. The thorough removal of contaminants means that the dissolution process can most probably produce highly purified plastics which meet food-grade specifications (although the process needs to be approved first for these applications).

Now it is time to take the next step of realising a full scale plant to demonstrate its value for the various clients. In order to convince both these clients, governments and the required investors, it is key to show the sustainable impact of the process in a both objective and quantitative manner and compare it with current references and alternative process routes for recycling. The methodology of an LCA is the most suited way to achieve this.'

2 Goal and scope

2.1 Goal and approach

The goal of this screening LCA is to estimate the carbon footprint of recycling three different selected waste streams with the SPEX dissolution process at 20 kt/yr product scale. These waste streams are:

1. HDPE from mixed post-consumer waste;
2. Laminate packaging (PP/PET/aluminium) from mixed post-consumer waste;
3. Breathing tubes (PP/LDPE/copper) from hospitals.

These waste streams are illustrative of different strategies to utilise the SPEX process. HDPE and laminate packaging are both present in post-consumer waste streams. While plastic sorting typically already generates a HDPE waste stream for mechanical recycling, laminate packaging is typically not separated yet (as it is complex to mechanically recycle). In contrast, medical breathing tubes can be collected at hospitals. The combination of PP and LDPE can be extracted together using SPEX Technology's process and can be reused to create new breathing tubes in a 'closed-loop solution' without any contamination from other waste materials.

Table 1 lists the compositions and further system descriptions for the three feedstocks used. This is further explained in the remainder of this chapter.

Table 1 - System description

	1. HDPE plastics	**2. Laminate packaging**	**3. Breathing tubes**
Input	HDPE waste – *97% HDPE* – *2% PET* – *1% additives*	Laminate packaging – *70% PP* – *28% PET + pigments* – *2% aluminium*	Breathing tubes – *37.5% PP* – *37.5% LDPE* – *13% copper* – *12% inorganic additives*
Product perspective analysis			
Functional unit	Production of HDPE	Production of PP	Production of breathing tube materials
Reference systems	Fossil HDPE production	Fossil PP production	Primary production of breathing tube materials
Waste perspective analysis			
Functional unit	Waste treatment of HDPE waste	Waste treatment of laminate packaging	Waste treatment of breathing tubes
Reference systems	Mechanical recycling Incineration	Incineration	Incineration
SPEX treatment system			
Main product	Recycled HDPE	Recycled PP	Recycled PP/PE mixture
Co-product	N.a.	Aluminium	Copper
Material losses to incineration	PET Additives (modelled as PET)	PET (+pigments)	Residue (modelled as inorganic materials)
Collection and sorting included	Yes	Yes	No
Additional analysis	N.a.	Recycling of PET losses using depolymerisation	N.a.

Screening carbon footprint approach

This study concerns a screening LCA of the SPEX process. As the process is not yet operated at the 20 kt/yr scale, primary process data is based on the mass- and energy balances of the conceptual design study of SPEX for full-scale operation. Literature data and assumptions are used to model background processes (e.g. collection and sorting).

In addition, note that this LCA focuses on the dissolution process' carbon footprint performance, i.e. its contribution to climate change due to the emission of greenhouse gases. Other environmental indicators are not included.

Product and waste perspective

The SPEX technology has two functions: treatment of plastic waste and production of new plastics. Therefore, the carbon footprint of the technology is analysed from two perspectives, the waste perspective and the product perspective.

From the waste perspective, the treatment of plastic waste streams by SPEX is compared to conventional waste treatment technologies (incineration, mechanical recycling). This perspective is relevant for policymakers interested in comparing the environmental implications of treating waste in different installations.

In the product perspective, the production of plastics by SPEX is compared to conventional plastic production (from fossil feedstock or by mechanical recycling). This can be used in business-to-business communication with parties interested in sourcing recycled plastics produced by SPEX.

What are the similarities and differences between the product and waste perspective?
The product perspective and waste perspective analyses are based on the same underlying data. In addition, the SPEX process is modelled with similar system boundaries in both perspectives. For this reason, comparisons with reference technologies tend to lead to similar conclusions, regardless of the perspective used. This means that if one option performs best in a product perspective analysis, it typically also performs best from a waste perspective analysis.

However, there are two important differences in the perspectives, corresponding to the different questions and audiences they belong to (discussed above). These can affect how recycling technologies are viewed and what conclusions are drawn. They are:

- The functional unit is different. Due to losses and the presence of non-polyolefin materials, 1 tonne of plastic feedstock is not converted into 1 tonne of recycled polyolefins. Therefore, expressing the results per tonne of recycled polyolefin output (product perspective) or per tonne of plastic feedstock (waste perspective) changes the absolute values in the carbon footprint results.
- The reference cases are different. In both analyses, the reference case is the 'conventional alternative' to recycling; if recycling would not exist, this 'conventional' technology would be applied to produce or dispose of the plastic waste. In the product perspective, the reference is the virgin production of polyolefins. From the waste perspective, the reference is the incineration (with energy recovery) of the plastic waste. Because these two references differ substantially, the product or waste perspective affects how recycling is viewed.

Temporal and geographical scope

As SPEX is still in development, it is expected to take several years before a 20 kt /yr is operational. In the coming years, the carbon footprint of the electricity mix will be reduced through the further implementation of renewable energy sources, which will influence the carbon footprint of both SPEX and the reference systems. Furthermore, SPEX can use electricity instead of natural gas to supply its process heat. To analyse the effect of a more renewable energy system, we consider two scenarios:

1. Current energy supply: We assume the carbon footprint of the 2022 Dutch electricity mix. The heat used by SPEX is produced with natural gas. The energy recovered from incineration (of losses or in the reference system) replaces the average 2022 Dutch electricity production and heat from natural gas.
2. Renewable energy supply: The electricity mix is fully renewable and SPEX has electrified the heat production. The energy recovered from incineration (of losses or in the reference system) replaces renewable electricity and heat from natural gas. The model of conventional production of plastics remains unchanged.

These two scenarios provide initial insights into the extremes when it concerns renewable energy supply. In the near future, the amount of renewable energy will lie somewhere in between the two scenarios.

The analysis focuses on SPEX dissolution operating in the Netherlands (using the Dutch electricity mix and aligning with the Dutch collection and sorting system). Also, the reference systems (mechanical recycling of plastics and waste incineration) are assumed to take place in the Netherlands. For the conventional production of plastics, average European production data is used.

2.2 System boundaries

This study has a cradle-to-gate scope. The starting point of the analysis is a waste stream containing PE and/or PP plastics. This waste stream is assumed to be free of environmental/carbon footprint burdens. The end point of the analysis is the recycled plastics (or other products in the case of reference treatments) produced.

We analyse the carbon footprint of the SPEX system from two perspectives: the product perspective and the waste perspective.

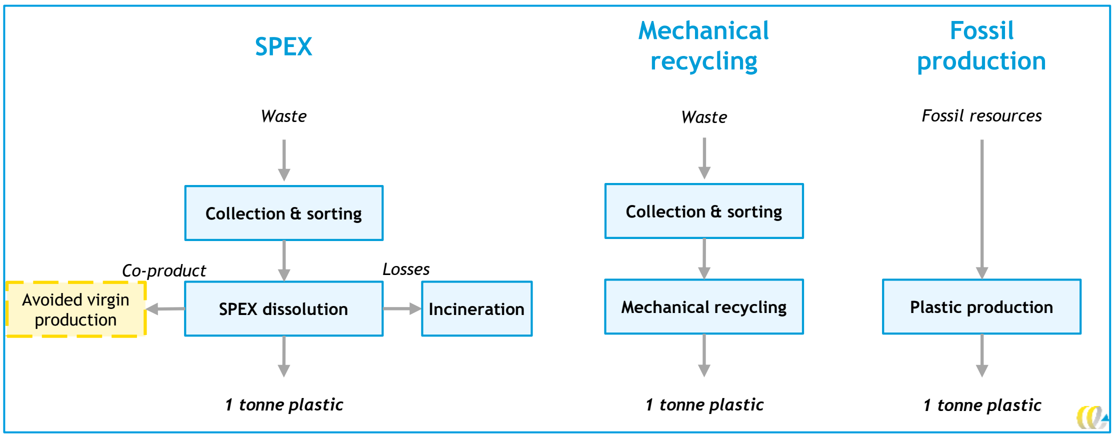
Product perspective

Figure 4 shows the system boundaries of the product perspective analysis. The functional unit of this analysis is the production of 1 tonne of plastics. Which type of plastic is produced depends on the feedstock (see Table 1 for the specifics for the three waste streams analysed in this study).

In the SPEX system, the process starts with collection and sorting of waste (if relevant). This is followed by the dissolution process of SPEX. In this process, electricity and heat are used as energy sources. During the process, some materials (both target material and non-target material) are lost. These materials are assumed to be incinerated with energy recovery. In addition to the main product, in some cases also one or more co-products are produced. Using the substitution approach, a credit is given for the avoided conventional production of these co-products.

In the product perspective, the production of plastics by SPEX is compared to the production of plastics from mechanical recycling and from fossil feedstock.

Figure 4 - System boundaries of product perspective analysis (generic)



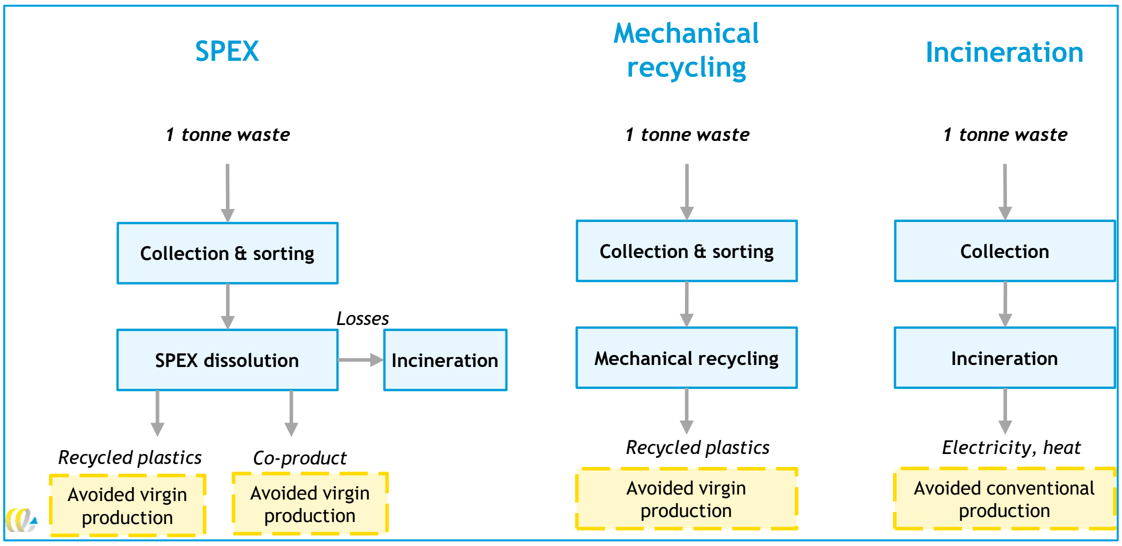
Waste perspective

Figure 5 shows the system boundaries of the waste perspective analysis. The functional unit of the analysis is the treatment of 1 tonne of waste (see composition in Table 1).

In the SPEX system, the process starts with collection and sorting of waste (if applicable). This is followed by the dissolution process of SPEX. In this process, electricity and heat are used as energy sources. During the process, some materials (both target material and non-target material) are lost. These materials are assumed to be incinerated with energy recovery. For all products produced by SPEX a credit is given for avoided conventional production (substitution approach).

Waste treatment by SPEX is compared to mechanical recycling (if relevant for the feedstock) and incineration. In the case of mechanical recycling, a credit is given for the avoided conventional production of plastics. If the feedstock is incinerated, energy and metals are recovered. A credit is given for the avoided conventional production of metal and energy.

Figure 5 - System boundaries of waste perspective analysis (generic)



2.3 Multifunctionality and allocation

The SPEX recycling process is a multi-output process. In addition to the target material (PE or PP), metals and PET can be recovered. The substitution approach is used to deal with these co-products, which means that a credit is given for avoided primary production of the recovered materials.

Furthermore, it can be noted here that in the product perspective analyses, no environmental credits are attributed to the PE/PP plastics produced by SPEX for avoiding incineration. Some product perspective recycling LCAs argue that recycling plastics avoids the incineration that would otherwise occur. The (avoided) carbon footprint of this incineration is then allocated to the recycled plastic product. However, it is not always evident that:

1. Incineration is the most reasonable reference treatment.
2. The final recycled product/producer is fully responsible for avoiding incineration.

For the first issue, it is not clear that the materials sent to recycling would otherwise be incinerated, as they can typically be treated in other end-of-life scenarios as well (e.g. landfilling, mechanical recycling, chemical recycling and incineration with carbon capture). Especially in forward-looking/ex-ante LCA studies for recycling technologies, attributing credits based on incineration is debatable, since non-circular end-of-life treatments of recyclable materials need to be phased out in a circular economy.

With regard to the second issue, other parties, including recyclers themselves, collection organisations and governments financially supporting recycling, may also ‘claim’ the avoided incineration, potentially causing double counting.

2.4 Data gathering and modelling

The foreground data on the SPEX process was provided by OBBOTEC, the developer of the SPEX dissolution process. This includes, for instance:

— composition of the feedstocks;

— energy and material inputs and outputs of the conceptual design of the SPEX process.

The data on the SPEX process is combined with secondary data on collection and sorting of waste. Also for the reference systems (fossil plastics production, waste incineration and mechanical recycling of HDPE) secondary data is used for the foreground data. Table 2 provides an overview of the data sources used for all processes.

Table 2 - Foreground data sources

Process	Used in analyses	Type of data	Data source
Collection and sorting	1, 2	Secondary data	CE Delft (CE Delft, 2021)
SPEX technology	1, 2, 3	Company-specific data	OBBOTEC
Fossil reference (product perspective)	1, 2, 3	Secondary data	Ecoinvent v3.10
Incineration reference (waste perspective)	1, 2, 3	Secondary data	Ecoinvent v3.10
Mechanical recycling reference	1	Secondary data	CE Delft
PET recycling (additional analysis)	2	Company-specific data	Ioniqa (CE Delft, 2018)

The foreground process data is combined with background data from the Ecoinvent (v3.10; cut-off system model) LCA database (Ecoinvent, 2024) and CE Delft data for the production of electricity (CE Delft, 2023).

The SimaPro 9.6 LCA software is used to model the processes and generate carbon footprint results. The carbon footprint results are calculated using the IPCC 2021 GWP100 (v1.03) method in SimaPro, taking a 100-year perspective on climate change impact.

3 Life cycle inventory

3.1 Collection and sorting

The HDPE packaging waste (feedstock 1) can be collected via both the source separation system (i.e. separate collection of plastics at households) and post separation system in the Netherlands (i.e. centralised sorting of plastics from mixed household waste). We use process data for the source separation system as a proxy for both systems.

Table 3 shows the inventory data for the collection and sorting of 1 tonne HDPE (after sorting). The data used to model the collection and sorting processes of HDPE packaging has been inventoried by CE Delft in 2015. The source of the inventory data is confidential.

Table 3 - Inventory data for collection and sorting of HDPE plastics per tonne of HDPE in the collected plastic waste

Processes/flows	Unit	Amount	Environmental impact modelling *Ecoinvent datasets shown in italics*
Transport municipal waste collection	tkm	50	*Municipal waste collection service by 21 metric ton lorry {CH}*
Transport to sorting and to recycling	tkm	370	*Transport, freight, lorry 16-32 metric ton, EURO6 {RER}*
Electricity	MJ	220	Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Incineration of PE sorting losses	kg	10	

Laminate packaging (feedstock 2) also requires collection and sorting, as this is a post-consumer waste stream. At the moment, laminate packaging is not sorted out for recycling. As a consequence, no process data for collection and sorting of laminate packaging is available yet. Therefore, we use the inventory data for collection and sorting of HDPE waste as a proxy for collection and sorting of laminate packaging.

For breathing tubes (feedstock 3), no collection and sorting is assumed, as this is a closed-loop recycling system instead of post-consumer recycling.

3.2 SPEX recycling

The following tables show the details on the modelled inputs and outputs of the SPEX recycling process. Table 4 shows process data for treating HDPE packaging waste, Table 5 shows process data for treating laminated packaging waste, and Table 6 shows process data for treating medical breathing tubes. Note that data is shown separately for the product and waste perspectives.

Table 4 - Inventory data for the dissolution of HDPE packaging waste with the SPEX technology in the product perspective (per tonne of HDPE output) and in the waste perspective (per tonne of HDPE waste input)

Processes/flows	Unit	Amounts		Environmental impact modelling
		Product perspective	Waste perspective	*Ecoinvent datasets shown in italics*
Input				
Feedstock	kg	1,054	1,000	Composition: – *97% HDPE* – *2% PET* – *1% others/additives*
Electricity	kWh	289	275	Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Heat	kWh	970	921	Current energy supply: Heat, from steam, in chemical industry {RER}| market for Renewable energy supply: Heat produced with an e-boiler with an efficiency of 99%, running on renewable electricity
Solvent	kg	0.53	0.50	*Assumed proxy: Hexane {GLO}| market for*
Nitrogen	kg	23	21	*Nitrogen, liquid {RER}| market for*
Output				
HDPE	kg	1,000	949	In the waste perspective the production of HDPE avoids: *Polyethylene, high density, granulate {RER}| polyethylene production*
HDPE losses	kg	22	21	Incineration with energy recovery (see Section 3.2.1)
PET losses	kg	21	20	Incineration with energy recovery (see Section 3.2.1)
Others/additives	kg	11	10	Incineration with energy recovery, modelled as incineration of PET (see Section 3.2.1)
Emission of nitrogen	kg	23	21	Nitrogen emitted to air as N_2, not included in the model, as this does not have an environmental impact

Table 5 - Inventory data for the dissolution of laminated packaging waste with the SPEX technology in the product perspective (per tonne of PP output) and in the waste perspective (per tonne of laminated packaging input)

Processes/flows	Unit	Amounts		Environmental impact modelling
		Product perspective	Waste perspective	*Ecoinvent datasets shown in italics*
Input				
Feedstock	kg	1,460	1,000	Composition: – *70% PP* – *28% PET + pigments* – *2% aluminium*
Electricity	kWh	395	271	Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Heat	kWh	970	664	Current energy supply: Heat, from steam, in chemical industry {RER}| market for

Processes/flows	Unit	Amounts		Environmental impact modelling
		Product perspective	Waste perspective	*Ecoinvent datasets shown in italics*
				Renewable energy supply: Heat produced with an e-boiler with an efficiency of 99%, running on renewable electricity
Solvent	kg	0.53	0.36	*Assumed proxy: Hexane {GLO}| market for*
Nitrogen	kg	21	15	*Nitrogen, liquid {RER}| market for*
Output				
PP	kg	1,000	685	In the waste perspective the production of HDPE avoids: *Polypropylene, granulate {RER}| polypropylene production*
Aluminium	kg	29	20	1 tonne of aluminium output avoids: 0.97 tonne of *Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| aluminium production*
PP losses	kg	22	15	Incineration with energy recovery (see Section 3.2.1)
PET losses	kg	409	280	Incineration with energy recovery (see Section 3.2.1)
Others/additives	kg	11	10	Incineration with energy recovery, modelled as incineration of PET (see Section 3.2.1)
Emission of nitrogen	kg	23	15	Nitrogen emitted to air as N_2, not included in the model, as this does not have an environmental impact

Table 6 - Inventory data for the dissolution of breathing tubes with the SPEX technology in the product perspective (per tonne of breathing tube materials output) and in the waste perspective (per tonne of breathing tubes input)

Processes/flows	Unit	Amounts		Environmental impact modelling
		Product perspective	Waste perspective	*Ecoinvent datasets shown in italics*
Input				
Feedstock	kg	1,000	1,000	Composition: – 37.5% PP – 37.5% LDPE – 13% copper – 12% inorganic additives
Electricity	kWh	272	272	Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Heat	kWh	712	712	Current energy supply: Heat, from steam, in chemical industry {RER}| market for Renewable energy supply: Heat produced with an e-boiler with an efficiency of 99%, running on renewable electricity
Solvent	kg	0.39	0.39	*Assumed proxy: Hexane {GLO}| market for*
Nitrogen	kg		17	*Nitrogen, liquid {RER}| market for*
Primary PP	kg	8	N.a.	New PP required to compensate for losses. *Polypropylene, granulate {RER}| polypropylene production*
Primary LDPE	kg	8	N.a.	New LDPE required to compensate for losses.

Processes/flows	Unit	Amounts		Environmental impact modelling
		Product perspective	Waste perspective	*Ecoinvent datasets shown in italics*
				Polyethylene, low density, granulate {RER}| polyethylene production
Primary inorganic additives	kg	120	N.a.	Production of new additives, assumed clay. *Kaolin {RER}| kaolin production*
Output				
PP	kg	367	367	In the waste perspective the production of HDPE avoids: *Polypropylene, granulate {RER}| polypropylene production*
LDPE	kg	367	367	In the waste perspective the production of HDPE avoids: *Polyethylene, high density, granulate {RER}| polyethylene production*
Copper	kg	130	130	In the waste perspective the production of 1 tonne of recovered copper avoids: 0.76 tonne of *Copper, anode {RU}| smelting of copper concentrate, sulfide ore*
Residue (inorganic additive)	kg	120	120	Incineration with energy recovery (see Section 3.2.1)
PP losses	kg	8	8	Incineration with energy recovery (see Section 3.2.1)
PE losses	kg	8	8	Incineration with energy recovery (see Section 3.2.1)
Emission of nitrogen	kg	17	17	Nitrogen emitted to air as N_2, not included in the model, as this does not have an environmental impact

3.2.1 Incineration of losses

All material losses from the dissolution process are incinerated with energy recovery. The incineration of materials results in CO_2 emissions (Table 7), which are based on stoichiometric calculations.

The amount of energy recovered depends on the recovery efficiency of the waste incinerator (Table 8) and the lower heating value of the materials incinerated (LHV) (Table 7). The energy produced is assumed to replace conventional electricity and heat production (Table 8).

Table 7 – Modelling details for the incineration of losses

Material	LHV (MJ/kg)	CO_2 emissions (kg CO_2-eq./kg)
PE	42.5	3.14
PP	32.8	3.14
PET	23.0	2.29
Residue (inorganic additive)	0	0

Table 8 - Modelling details for energy recovery

Processes/flows	Efficiency	Environmental impact modelling *Ecoinvent datasets shown in italics*
Electricity generated	18%	Avoided electricity production: Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Heat generated	31%	Avoided heat production: *Heat, district or industrial, natural gas {Europe without Switzerland}| market for*

3.3 Fossil reference (product perspective)

In the product perspective analysis, the production of plastics by SPEX technology from HDPE waste and laminated packaging (feedstock 1 and 2) is compared to the production of fossil plastics.

In the case of the breathing tubes, the closed loop recycling to produce 1 tonne of breathing tubes by SPEX technology (feedstock 3) is compared to the conventional production of material for 1 tonne of breathing tubes.

The modelling details of the fossil or conventional reference products are shown in Table 9.

Table 9 - Modelling details of the fossil reference product for the product perspective analyses

	Amount (tonne)	Fossil reference *Ecoinvent datasets shown in italics*
1. HDPE production	1	*Polyethylene, high density, granulate {RER}| polyethylene production*
2. PP production	1	*Polypropylene, granulate {RER}| polypropylene production*
3. Material for breathing tubes	1	– 0.375 tonne *Polypropylene, granulate {RER}| polypropylene production, granulate* – 0.375 tonne *Polyethylene, low density, granulate {RER}| polyethylene production* – 0.13 tonne *Copper, anode {RU}| smelting of copper concentrate, sulfide ore* – 0.12 tonne *Kaolin {RER}| kaolin production*

3.4 Incineration reference (waste perspective)

The waste perspective analysis compares recycling via SPEX technology to the incineration with energy recovery of the three feedstocks at a Dutch MSWI. The incineration process results in an environmental impact from transport and the direct CO_2 emissions, and in an avoided environmental impact because of the recovery of energy and metals.

In the tables below the inventory data of incineration of HDPE packaging waste (Table 10), laminated packaging (Table 11) and breathing tubes (Table 12) is shown.

Table 10 - Inventory data for the incineration with energy recovery of HDPE packaging waste in a Dutch MSWI (per tonne of HDPE waste input)

Processes/flows	Unit	Amounts	Environmental impact modelling *Ecoinvent datasets shown in italics*
Input			
Feedstock	kg	1,000	Composition: – 97% HDPE – 2% PET – 1% others/additives
Transport	tkm	100	*Municipal waste collection service by 21 metric ton lorry {CH}|*
Output			
Electricity	GJ	7.54	Avoided electricity production: Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Heat	GJ	12.99	Avoided heat production: *Heat, district or industrial, natural gas {Europe without Switzerland}| market for*
CO_2 emissions to air	kg	3,117	

Table 11 - Inventory data for the incineration with energy recovery of laminated packaging waste in a Dutch MSWI (per tonne of laminated packaging waste input)

Processes/flows	Unit	Amounts	Environmental impact modelling *Ecoinvent datasets shown in italics*
Input			
Feedstock	kg	1,000	Composition: – 70% PP – 28% PET + pigments – 2% aluminium
Transport	tkm	100	*Municipal waste collection service by 21 metric ton lorry {CH}|*
Output			
Electricity	GJ	5.29	Avoided electricity production: Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Heat	GJ	9.11	Avoided heat production: *Heat, district or industrial, natural gas {Europe without Switzerland}| market for*
Aluminium	kg	14	Recovery efficiency of aluminium from bottom ash: 69% (Afvalfonds Verpakkingen, 2021) 1 tonne of aluminium output avoids: 0.97 tonne of *Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| aluminium production*
CO2 emissions to air	kg	2,842	

Table 12 - Inventory data for the incineration with energy recovery of discarded breathing tubes in a Dutch MSWI (per tonne of breathing tubes input)

Processes/flows	Unit	Amounts	Environmental impact modelling *Ecoinvent datasets shown in italics*
Input			
Feedstock	kg	1,000	Composition: – 37.5% PP – 37.5% LDPE – 13% copper – 12% residue (inorganic additives)
Transport	tkm	100	*Municipal waste collection service by 21 metric ton lorry {CH}|*
Output			
Electricity	GJ	5.08	Avoided electricity production: Current energy supply: 2022 Dutch electricity mix (CE Delft, 2023) Renewable energy supply: mix of electricity from wind and solar energy
Heat	GJ	8.75	Avoided heat production: *Heat, district or industrial, natural gas {Europe without Switzerland}| market for*
Copper	kg	109	Recovery efficiency of copper from bottom ash: 84% (Afvalfonds Verpakkingen, 2021) 1 tonne of copper output avoids: 0.76 tonne of *Copper, anode {RU}| smelting of copper concentrate, sulfide ore*
CO_2 emissions to air	kg	2,357	

3.5 Mechanical recycling

The SPEX recycling of HDPE packaging waste (feedstock 2) is compared to mechanical recycling of HDPE packaging waste, in both the product and waste perspectives.

The model of mechanical recycling consists of two processes:
- Collection and sorting of HDPE packaging waste: the model of this process is described in Section 3.1.
- Mechanical recycling of HDPE packaging waste: this model is based on data inventoried by CE Delft in 2015. The source of the inventory data and the inventory data itself is confidential.

The HDPE output of the mechanical recycling process is assumed to replace fossil HDPE production (ecoinvent dataset: *Polyethylene, high density, granulate {RER}| polyethylene production*).

3.6 Depolymerisation of PET output (feedstock 2)

In the main analysis of the dissolution of laminated packaging (feedstock 2) we assume that the PET output is incinerated with energy recovery. Alternatively, the PET could be recycled using a depolymerisation technology. This option is studied in the additional analysis described in Section 4.2.1.

We model the depolymerisation of PET using results from the Ioniqa screening carbon footprint assessment (CE Delft, 2018), as an illustrative depolymerisation process.

As the precise amount of pigments in the PET is unknown, we assume that the PET waste stream sent to depolymerisation consists of 100% PET. In reality, part of the PET stream will consist of pigments, which are removed in the depolymerisation process. The PET yield of the depolymerisation process will therefore be lower than modelled here.

The PET output of the depolymerisation process is assumed to replace fossil bottle grade PET production (ecoinvent dataset: *Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production*).

4 Results

This chapter provides the carbon footprint results. We discuss the results per feedstock, starting with the HDPE plastic waste (Section 4.1), followed by the laminated packaging (Section 4.2) and finishing with the breathing tubes (Section 4.3). For each feedstock, we first discuss the product perspective results, followed by the waste perspective results.

All results shown below are cradle-to-gate results. For SPEX technology (and mechanical recycling) all processes starting from where the waste feedstocks are generated (e.g. HDPE waste in households) are included in the results.

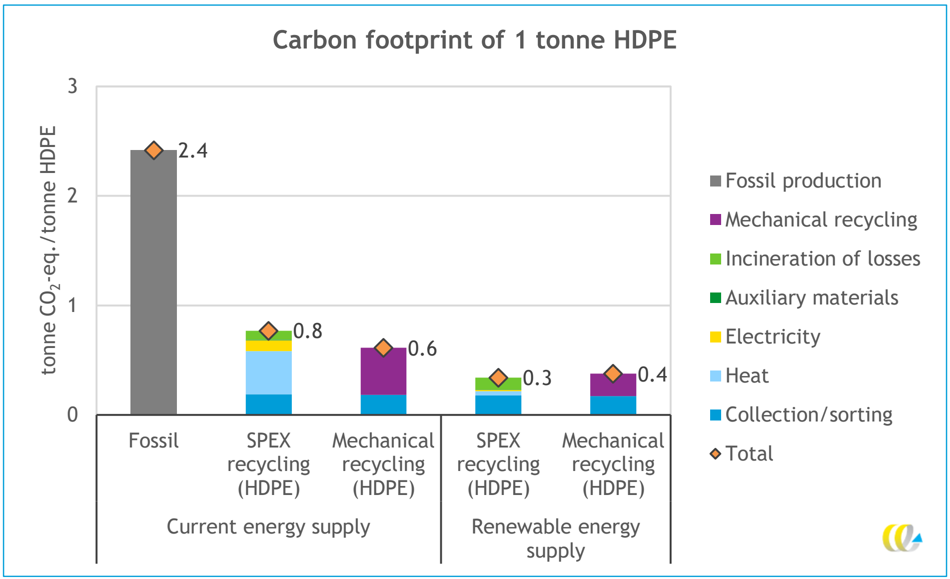
For all results shown in this chapter, lower values are better, as these represent a lower environmental impact.

4.1 HDPE plastic waste

Product perspective

Figure 6 shows the carbon footprint of 1 tonne of HDPE produced by SPEX, mechanical recycling and from fossil resources (newest Ecoinvent data). The left three bars show the results when using the current average energy supply. The right three bars show the results when a renewable energy mix is used for SPEX recycling and mechanical recycling.

Figure 6 - Carbon footprint of HDPE production (cradle-to-gate) - recycling of HDPE waste



The carbon footprint of HDPE produced via SPEX is substantially lower (a reduction of 1.6 t CO_2-eq./t) than the carbon footprint of fossil HDPE. The carbon footprint reduction is increased further (2.1 t CO_2-eq./t) with a renewable energy mix.

Compared to mechanically recycled HDPE, the carbon footprint of HDPE from SPEX recycling is estimated to be slightly higher with the current energy supply. When using renewable energy, the carbon footprints are comparable. However, electrification of mechanical recycling is not considered in the analysis. When comparing SPEX and mechanical recycling, it must be noted that the quality of the HDPE produced with the SPEX technology is expected to be higher as more contaminations can be removed.

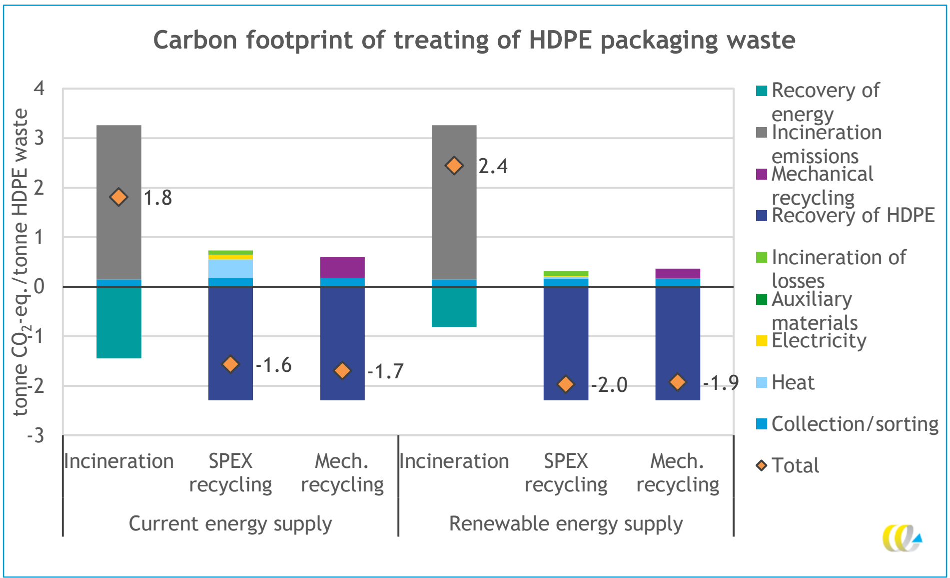
With the current energy supply, the carbon footprint of the SPEX technology stems primarily from the use of heat and the collection and sorting processes. The use of electricity and the incineration of losses make up the rest of the carbon footprint. With a renewable energy supply, only the carbon footprint contributions of collection and sorting and incineration of losses remain substantial.

Waste perspective

Figure 7 shows the carbon footprint of the waste treatment of HDPE waste with SPEX, mechanical recycling or incineration with energy recovery. The left three bars show the results when using the current average energy supply for all technologies. The right bars show the results when a renewable energy mix is used.

All components above the horizontal axis have a climate impact, whereas the components below the horizontal axis represent avoided climate impact. A net negative carbon footprint means that the amount of avoided greenhouse gas emissions is larger than the amount of emitted greenhouse gas emissions.

Figure 7 - Carbon footprint of waste treatment of HDPE waste



The carbon footprint of waste treatment with SPEX technology is substantially lower (reduction of 3.4 t CO_2-eq./t) than the carbon footprint of incineration with energy recovery. The carbon footprint reduction increases (4.4 t CO_2-eq./t) with a renewable energy mix. This is partly due to the increase in the carbon footprint of incineration, which receives less credits for avoiding cleaner energy generation (renewable energy scenario) than more fossil energy (current energy scenario).

The carbon footprint of mechanical recycling of HDPE waste is comparable to the carbon footprint of SPEX technology. The carbon footprint of both technologies is dominated by the credit for recovery of HDPE and the resulting avoided fossil HDPE production. It must be noted that the HDPE produced with mechanical recycling can have a lower quality than fossil HDPE and cannot replace fossil HDPE in all application. The HDPE produced with SPEX technology, on the other hand, is similar to the quality of fossil HDPE. This potential quality difference has not been taken into account in the environmental credits, as both types of recycled HDPE can replace primary HDPE production in specific product applications.

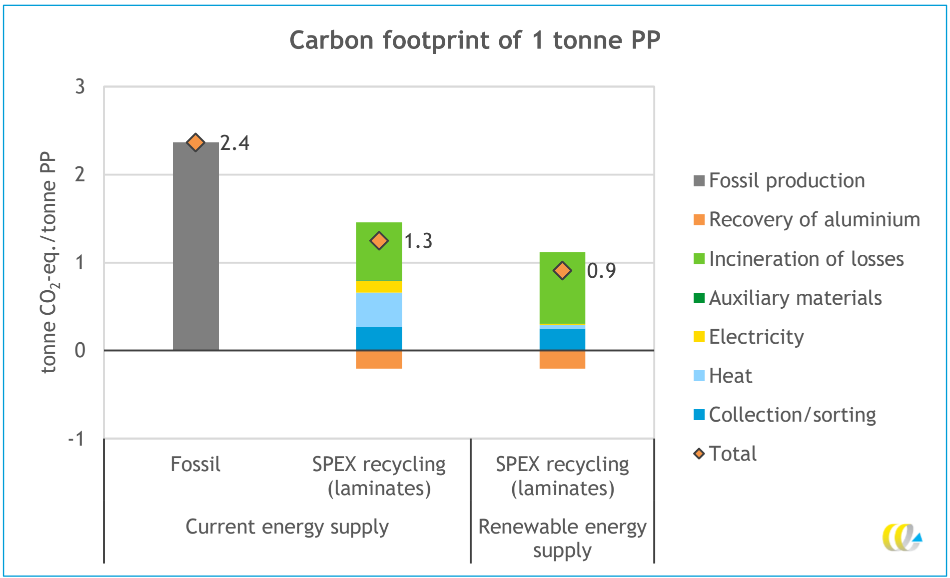
4.2 Laminated packaging

Product perspective

Figure 8 shows the carbon footprint of 1 tonne of PP produced via SPEX recycling of laminated packaging and fossil PP. The carbon footprint of PP produced with SPEX recycling is substantially lower (reduction of 1.1 t CO_2-eq./t) than the carbon footprint of fossil PP. The carbon footprint reduction increases (1.5 t CO_2-eq./t) with a renewable energy mix.

With the current energy supply, the carbon footprint of the SPEX technology is dominated by the use of heat in the incineration of losses (mostly PET, which accounts for 28%wt. of the feedstock). With a renewable energy supply, the carbon footprint of heat decreases considerably. The carbon footprint of the incineration of losses, on the other hand, increases with a renewable energy supply, as the credit for energy recovery decreases.

Figure 8 - Carbon footprint of PP production (cradle-to-gate) - recycling of laminate packaging

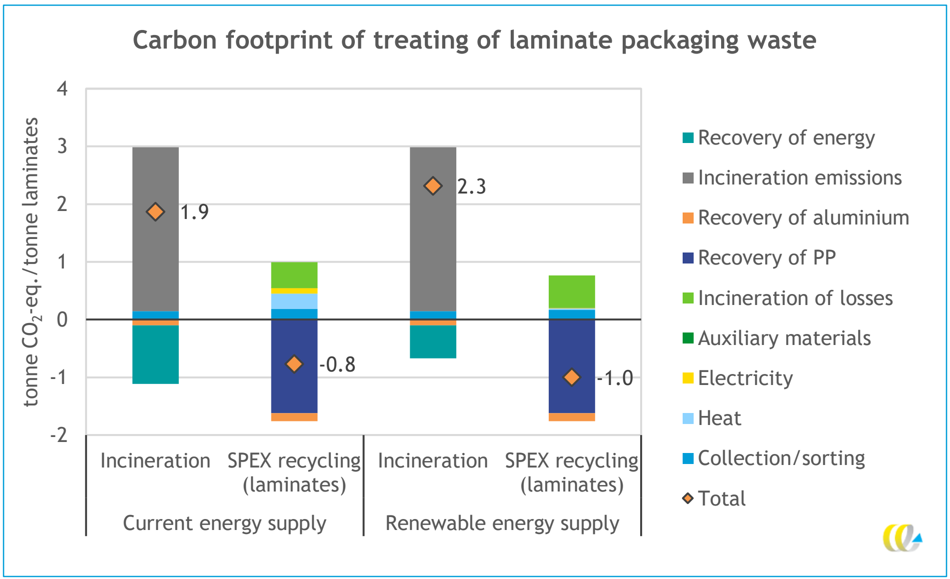


Waste perspective

Figure 9 shows the carbon footprint of the waste treatment of laminated packaging with SPEX recycling and incineration with energy recovery. The left two bars show the results when using the current average energy supply for all technologies. The right two bars show the results when renewable energy is used.

Waste treatment with SPEX recycling results in a 2.7 t CO_2-eq./t lower carbon footprint than incineration. The carbon footprint reduction is even higher (3.3 t CO_2-eq./t) with a renewable energy mix. The carbon footprint of the SPEX technology is dominated by the credit for the recovery of PP and the resulting avoided fossil PP production.

Figure 9 - Carbon footprint of waste treatment of laminate packaging



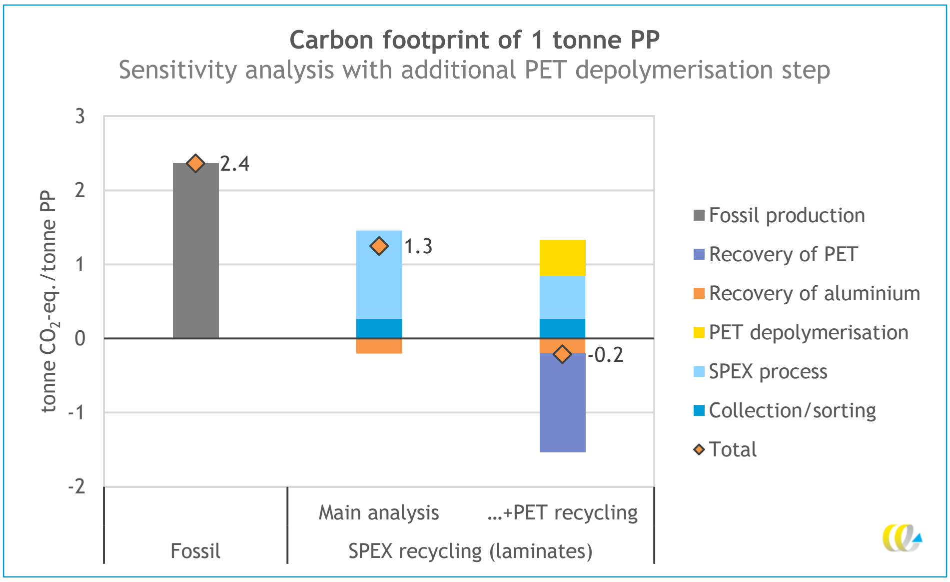
4.2.1 Additional analysis: PET recycling

In this analysis, the PET that is recovered during SPEX recycling of laminates is assumed to be treated with depolymerisation, a novel form of chemical recycling. The methodological details for this additional analysis are provided in Section 3.6.

Product perspective

Figure 10 shows the carbon footprint results in the product perspective. The combination of SPEX recycling with PET depolymerisation is shown on the right. While the PET depolymerisation process results in greenhouse gas emissions, it also generates an environmental credit due to the recovery of PET which can substitute fossil PET production. The result is that the estimated carbon footprint of recycling is lowered from 1.3 t CO_2-eq./t PP produced to -0.2 t CO_2-eq./t PP. This shows the added value of combining and/or cascading different novel recycling technologies.

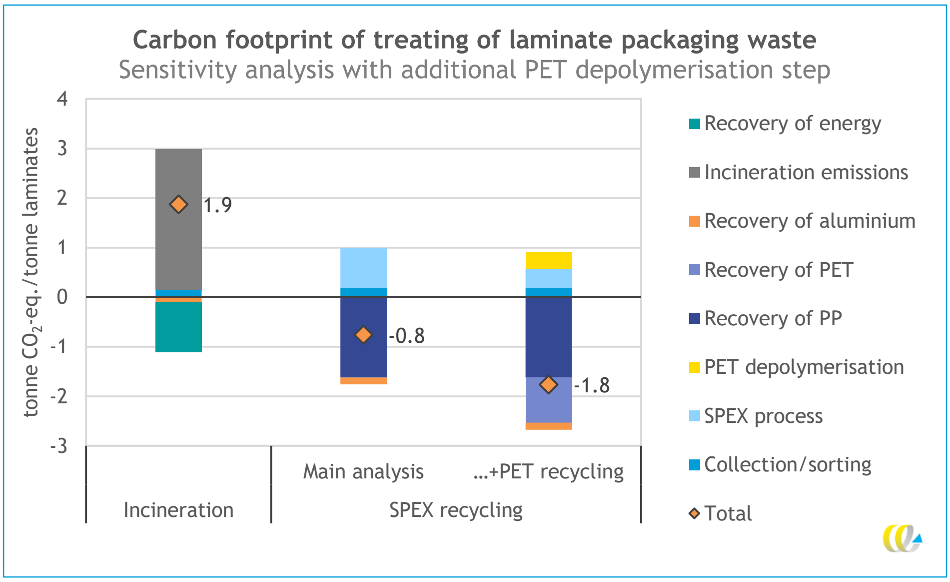
Figure 10 - Carbon footprint of PP production (cradle-to-gate) - recycling of laminate packaging, with additional PET depolymerisation



Waste perspective

The same analysis is conducted using the waste perspective, as shown in Figure 11. As in the product perspective, the additional recycling of PET results in a larger environmental credit for PET recovery. The estimated carbon footprint is reduced from -0.8 t CO_2-eq./t laminated packaging when only using SPEX to -1.8 t CO_2-eq./t laminates when using both technologies.

Figure 11 - Carbon footprint of waste treatment of laminated packaging, with additional PET depolymerisation

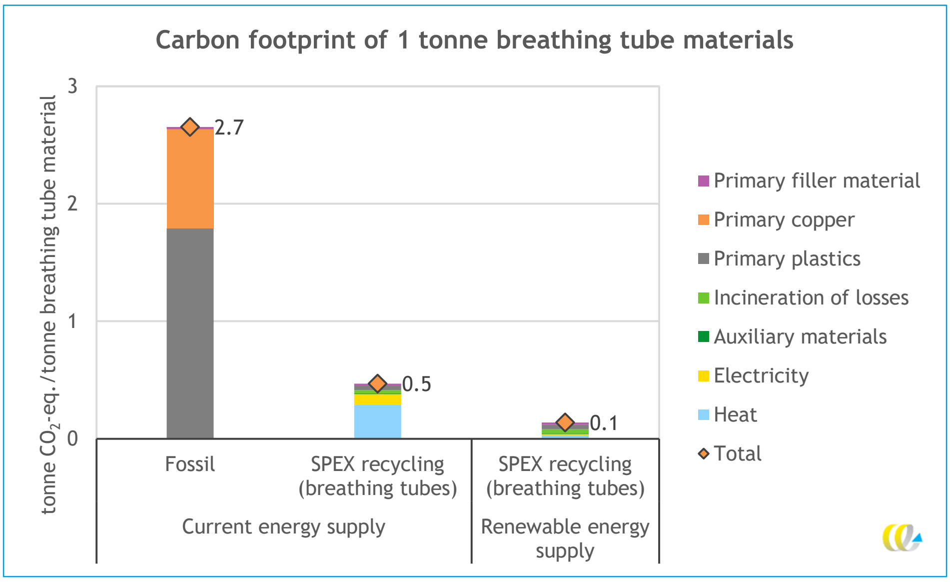


4.3 Breathing tubes

Product perspective

Figure 12 shows the product perspective results for breathing tube materials (PP, LDPE, copper and inorganic additives). The 'fossil' production route represents the primary production of all these materials. When using SPEX recycling, the PP, LDPE and copper can be fully recovered and used for the production of new breathing tubes, as this is a closed-loop recycling system. The estimated carbon footprint reduction when using the current energy supply is about 2.2 t CO_2-eq./t materials produced. When using renewable energy supply, the carbon footprint of heat and electricity used are almost fully reduced. This results in an estimated carbon footprint reduction of 2.6 t CO_2-eq./t materials produced compared to fossil production.

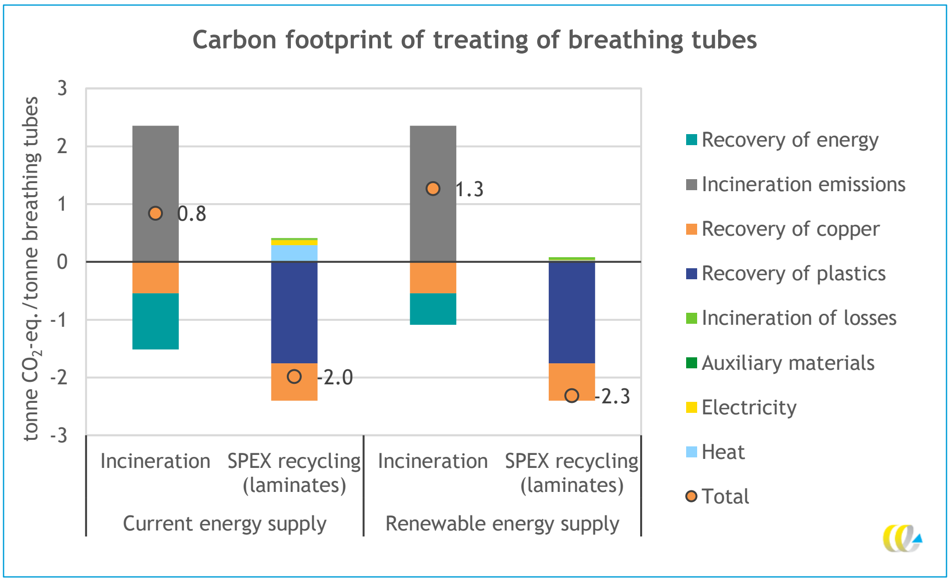
Figure 12 - Carbon footprint of HDPE production (cradle-to-gate) - recycling of breathing tubes



Waste perspective

Figure 13 shows the results for the waste treatment of breathing tubes. The incineration route results in direct emissions, but also recovers copper and energy (from the incineration of plastics). In contrast, SPEX has far lower direct emissions, also recovers the copper fraction, but also recovers the PP and LDPE plastics which results in a substantial environmental credit. The estimated carbon footprint reduction is about 2.8 t CO_2-eq./t breathing tubes. The reduction is increased to about 3.6 t CO_2-eq./t breathing tubes when using renewable energy.

Figure 13 - Carbon footprint of waste treatment of breathing tubes



5 Conclusion and discussion

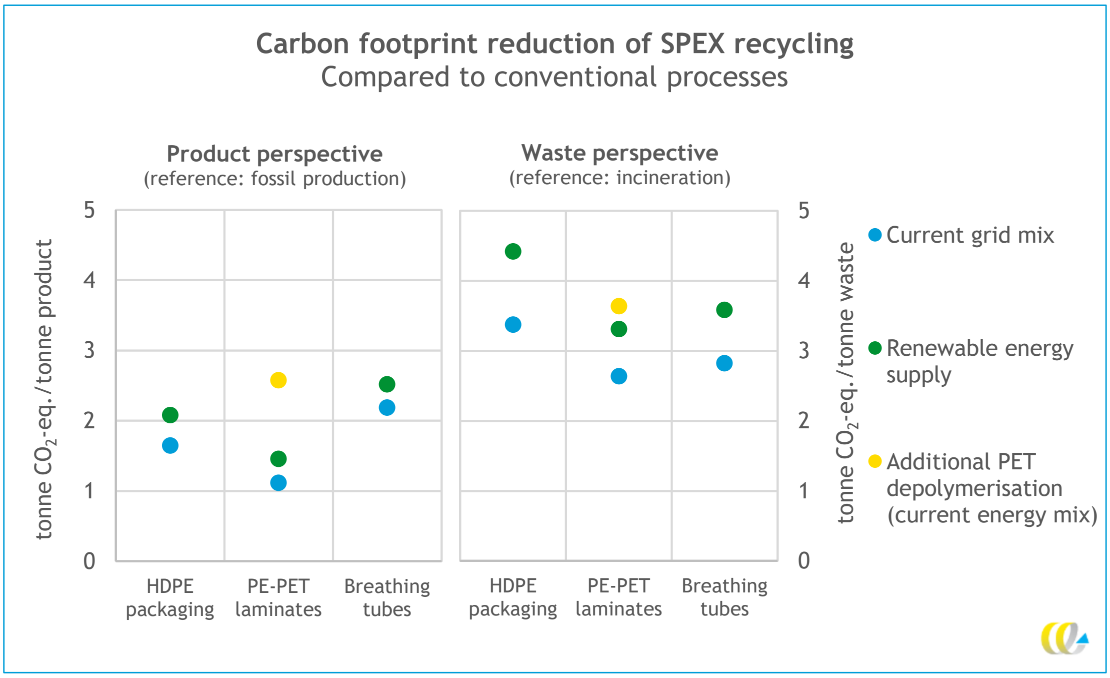
This screening LCA estimates the carbon footprint of the SPEX polyolefin dissolution process. The study covers three plastic waste feedstocks (HDPE waste, laminate packaging and breathing tubes) and includes different perspectives and reference treatments of plastic waste.

Process data for dissolution was provided by SPEX for the projected full scale (20 kt/yr) operation. This is combined with literature data and assumptions for background processes (see also limitations below).

Results and conclusions

In Figure 14, the carbon footprint results for all studied cases are summarized. The figure shows the carbon footprint reduction achieved by SPEX recycling compared to the main reference technology. Higher values represent larger carbon footprint reductions.

Figure 14 - Overview of estimated carbon footprint reductions of SPEX recycling, per tonne output (product perspective) or per tonne waste input (waste perspective)



The analysis shows that SPEX recycling has a substantially lower (1.1 to 1.9 t CO_2-eq./t) estimated carbon footprint than fossil production of polyolefins (product perspective analyses, current energy mix). This reduction is increased further to 1.5 to 2.2 t CO_2-eq./t when assuming renewable energy supply for SPEX.

The reduction is largest when treating medical breathing tubes, which can be fully recycled with SPEX dissolution. In contrast, the reduction is smallest for packaging laminates, where PET and additives are lost to incineration.

From the waste perspective analyses, the estimated carbon footprint reductions achieved by SPEX follow the same trends. However, the reductions are higher, as these results also include a credit for avoided fossil production of the recovered materials (see discussion in Section 2.2). The waste perspective reductions range from 2.6 to 3.4 t CO_2-eq./t waste treated when using the current energy mix, and 3.3 to 4.5 t CO_2-eq./t waste treated when using renewable energy for SPEX dissolution.

The low carbon footprint of SPEX dissolution is caused by its comparatively low energy consumption and limited use of auxiliary materials (including high solvent recovery). The key contributors to its carbon footprint are heat consumption (especially when using current, non-renewable energy), losses of non-target materials (i.e. PET and additives when treating laminated packaging), and collection and sorting before SPEX treatment.

It should be noted here that losses of non-target materials result in a higher carbon footprint when these materials are sent to incineration. However, the analysis of the combination of SPEX recycling with PET depolymerisation (yellow dots in Figure 14) highlights that combining novel recycling technologies can result in even larger carbon footprint reductions. Other additional combinations can be envisioned as well, including the SPEX recycling of PE or PP losses that come from PET depolymerisation.

Uncertainties and recommendations

The screening LCA contains some important assumptions and other limitations. These can be addressed in future updates to increase the robustness of the conclusions presented here. Key limitations are:

- The analysis is primarily based on SPEX process data projected for 20 kt/yr operation. Once in operation, it is important to validate this data (energy consumption, solvent recovery rates, mass balances, etc.) in practice.
- The first product perspective analysis compares SPEX, mechanical recycling and fossil production routes of 1 tonne PE. However, the quality/purity of the products may not be fully identical and there can be regulatory limitations affecting whether a specific product can be used in specific applications (e.g. food contact). While the outputs of all three systems are likely interchangeable in many applications, it is relevant to consider quality differences in greater detail when analysing specific product applications.
- The screening LCA contains various assumptions and use of background data (as described in Chapter 3) which can be improved:
  - There are uncertainties in the material composition of the waste streams being treated by SPEX. For example, it is not known which additives are used in packaging laminates, so incineration of these materials has been modelled using proxy data. Similarly, additives in the breathing tubes are assumed to consist fully of inorganic filler materials (assumed to be clay) which do not contribute to the carbon footprint when incinerated. If these additives do contain carbon, this impact will change.
  - Collection and sorting is based on background data, which may not be fully representative
  - Laminates are not sorted out of residual household waste at the moment. This means that specific process data for sorting of laminates is not available. Data for collection and sorting of PE has been used as proxy data.

- No collection and sorting is assumed to be required for breathing tubes. Overall, transportation processes have been modelled at a high level, as their contribution is expected to be minor. This can be improved in future updates when studying more (site-)specific cases.
- Pretreatment of feedstocks has not been included in the analysis. According to SPEX, only a cold wash of the feedstock will be necessary. The contribution of this step to the total carbon footprint is expected to be small. However, it is possible that material losses occur during pretreatment, which could have a larger contribution to the carbon footprint.

— For the fossil production reference (in the product perspective), it was not possible to estimate the effect of more renewable energy supply. The conclusions for SPEX with renewable energy supply are therefore based on a comparison of fossil production with the current energy supply. Ideally, the potential carbon footprint reduction of using more renewable energy during the fossil production routes would be taken into account.

— This screening study focuses on the carbon footprint performance of different technologies. Additional environmental indicators can be included in a more extensive LCA.

— With heat being the primary contributor to the SPEX carbon footprint, electrification with use of renewable electricity offers the best potential for further reduction of the carbon footprint.

6 Literature

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A Introduction to LCA

Life cycle assessment (LCA) is a method to quantify the environmental impacts of products or services over their entire life cycle. ISO 14040/14044 have standardised LCA and introduced the LCA framework (ISO, 2006a, 2006b).

A.1 Why use life cycle assessment?

LCA takes into account the environmental impacts of all processes required to deliver a product or service. In doing so, LCA prevents the shifting of burdens. For example, in order to know whether an electric car or a car with an internal combustion engine is more sustainable, it is important to look beyond the direct emissions coming from the car itself, but also consider how the electricity used in the electric car was generated and how the fuels were supplied. By taking all relevant processes of the entire life cycle into account, LCA can be used to compare products or services[1] in a fair and transparent way.

A.1 How are LCAs conducted?

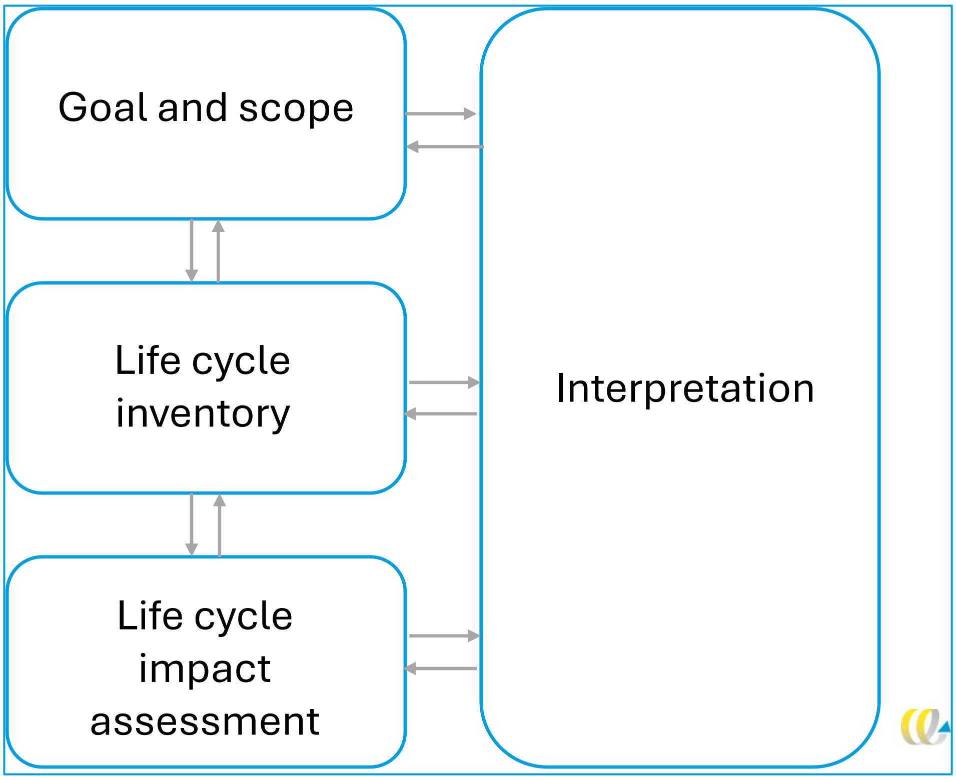
LCA studies are carried out in four phases, which are also shown in Figure 15:

- The **Goal and scope** phase defines:
  - What is assessed: the subject of study, also called the 'functional unit'. The final results of the LCA are expressed per functional unit.
  - Why and for whom the assessment is performed. This influences the desired level of detail, for example.
  - And how: which processes are taken into account (and which are not), i.e. the system boundaries of the study.
- **Life cycle inventory** gathers the required information, in line with the study's goal and scope, to determine the environmental impacts. This (crucial) phase is further described below.
- **Life cycle impact assessment** converts the gathered inventory data into environmental impact results. This is done using specialised LCA software.
- The **Interpretation** phase consists of the interpretation of the final results (What conclusions can we draw? What additional sensitivity analyses are needed?), but also consists of consistency checks (Is the inventory data in line with the LCA's scope? Are the impact assessment results appropriate for the goal?).

Life cycle assessment is an iterative process, indicated by the (two-directional) arrows in Figure 15. This means that findings and insights from the later phases may lead to changes in the choices made in earlier phases.

[1] The remainder of this text focuses on the application of LCA to products, as this is more intuitive, but the same principles apply to services.

Figure 15 - Life cycle assessment framework (adapted from ISO 14040)



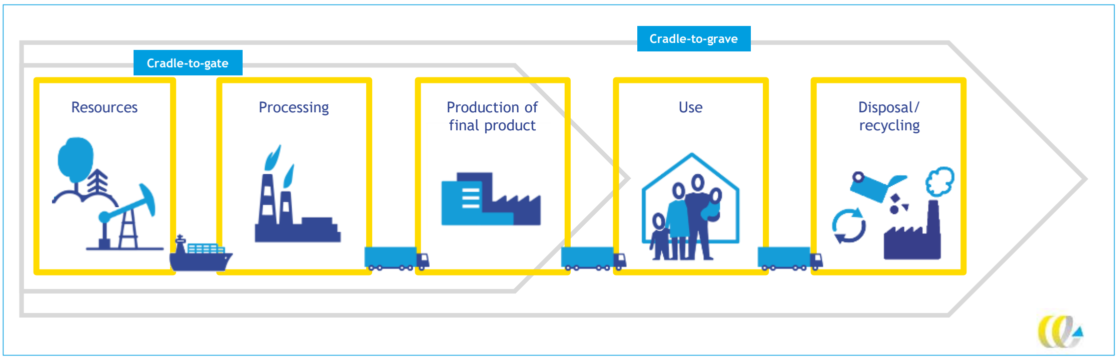
A.2 What system boundaries are used in LCA studies?

The system boundaries of an LCA refer to which processes are taken into account. The appropriate system boundaries depend on the goal of a study. Three terms are commonly used to describe the system boundaries applied, although these do not provide all information on the choices made (as explained further below):

1. In principle, LCA uses a **cradle-to-grave** scope, meaning that all relevant processes to deliver, use, and dispose of a product are included. For example, in the case of a consumer product, the following processes may be included: extraction of raw materials, processing, the production, and use of various auxiliary materials, various transportation steps, energy use, the use phase by a consumer, and final disposal and/or recycling (the end-of-life). The cradle-to-grave scope is relevant when a study intends to calculate the full environmental impact of a product, for example to understand the contribution of end-of-life disposal to the overall impacts.
2. In other cases, a **cradle-to-gate** scope is used, which means that processes beyond the manufacture of a final product (such as the use phase and final disposal) are not taken into account. Cradle-to-gate studies are for instance used when an LCA's goal is to compare the environmental impact of two alternative processes to create an identical product. In this example, the (environmental impact of the) use phase and disposal phase will be identical as well, so they do not need to be studied. Cradle-to-gate studies are also used when a manufacturer wants to provide information on one of its products to potential buyers. For example, polymers can be used for a wide variety of plastic formulations and applications, so a polymer manufacturer may provide cradle-to-gate results for others to use. This is done for instance in Environmental Product Declarations (EPDs).

3. Finally, **gate-to-gate** LCAs focus on only one process in the entire life cycle. These studies may for example focus on a process converting material A into material B, taking into account the energy requirements, use of auxiliary materials and emissions to the environment of this single process. However, the environmental impacts of producing raw material A and the further processing, use and disposal of material B, are not taken into account. Gate-to-gate LCAs can be linked together to create a more complete cradle-to-gate or cradle-to-grave LCA. However, this requires that the gate-to-gate studies are conducted using the same methodology. Furthermore, information on the mass flows between different processes is required.

Figure 16 - Simplified overview of cradle-to-gate and cradle-to-grave system boundaries in LCA

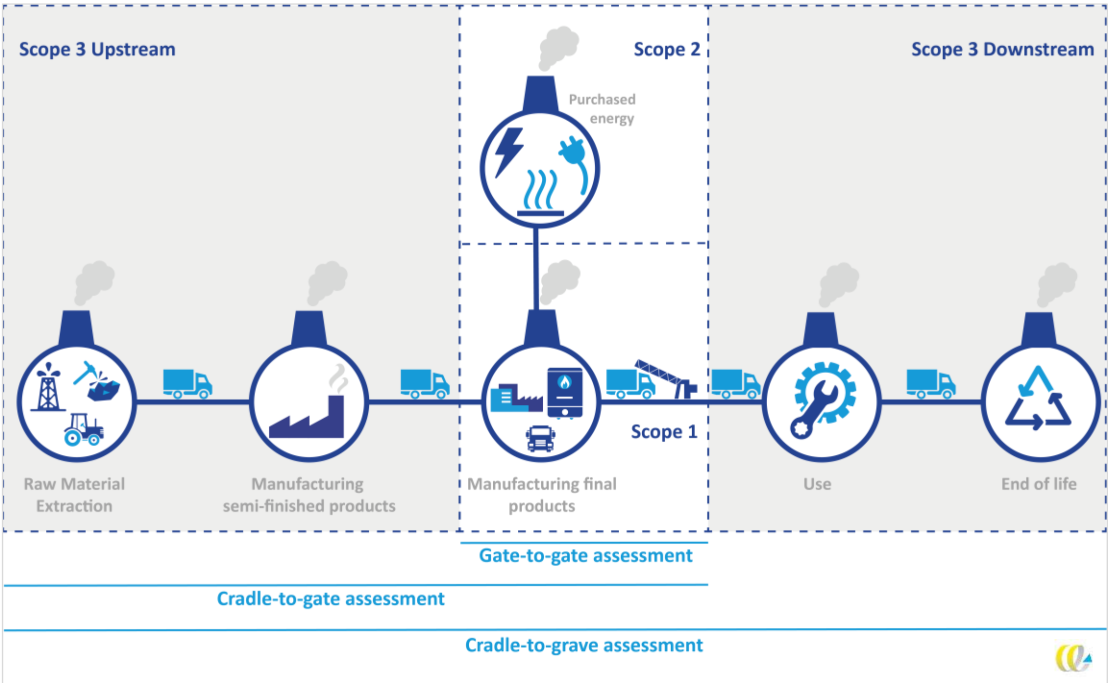


It should be noted that the system boundaries of an LCA are more complex than implied by the three categories presented above. While a complete, cradle-to-grave LCA includes the entire life cycle of a product, simplifications may still be made. For example, (the environmental impacts of) the production of capital goods (e.g. factories and machinery), transportation (as this is sometimes a minor contribution) or 'minor' processes are sometimes left out. Whether such simplifications are appropriate depends on the goal of the LCA (e.g. if the goal is to derive a rough first-estimate of the environmental impacts of a product, simplifications are more reasonable). Therefore, when interpreting the results of an LCA study, it is important to know the exact system boundaries that were used to derive them, as well as other methodological choices and assumptions made.

What do the terms 'Scope 1', 'Scope 2' and 'Scope 3' refer to?
In addition to terms like cradle-to-grave, LCAs and other studies sometimes refer to emissions in different *scopes*, i.e. Scope 1, Scope 2, and Scope 3. These terms originate in LCA methodologies specifically aimed at helping organisations to estimate their environmental impact, such as the Greenhouse Gas (GHG) Protocol (WRI & WBCSD, 2004) These terms are not typically used in LCAs of products or services.

The three scopes are illustrated in Figure 17 and can be defined as follows:
- **Scope 1**: direct emissions of the reporting organisation. For example: emissions from own installations (e.g. gas boilers) or emissions from the use of company-owned vehicles.
- **Scope 2**: (indirect) emissions belonging to purchased electricity, steam, heat or cooling of own installations.
- **Scope 3**: (indirect) emissions of upstream or downstream activities. This includes for instance the environmental impacts of purchased goods, transport and distribution, business travel, employee commuting, the use phase of products, disposal and waste treatment.

Figure 17 - Illustration of Scope 1, 2 and 3



A.3 How are environmental impact results calculated?

In the life cycle inventory LCA phase, a complete list of all emissions to the environment (and extractions from the environment) required to fulfil the functional unit is gathered. The life cycle inventory for instance includes all CO_2, CH_4 and N_2O emitted to the atmosphere. These emissions are then converted into one or more environmental impact indicators (during the third LCA phase: life cycle impact assessment). For example, the contribution to climate change is calculated by multiplying all emissions of greenhouse gases by their so-called global warming potential (GWP). This converts all emissions into CO_2-equivalents (eq.) so that they can be summed into one result (the ‘carbon footprint’).

The life cycle inventory corresponds to the scope and system boundaries used in the LCA, i.e. which processes are taken into account in the analysis. To derive the life cycle inventory, **process data** is gathered for all processes within the system boundaries, consisting of, for instance:
- energy use;
- material use, including auxiliary materials;
- waste streams generated (e.g. solid waste sent to incineration, polluted water);
- direct emissions to the environment (e.g. CO_2);
- direct extractions from the environment (e.g. resources such as river water, air, or coal).

Process data such as energy use, material use and waste generation shows how a process is linked to other production processes. For example, the auxiliary materials that a process uses are produced and supplied in a separate production chain. Each of the steps in this production chain has their own direct emissions and extractions that need to be taken into account. The final life cycle inventory is therefore the result of gathering all emissions and extractions over the entire ‘tree’ of linked processes.

To simplify this process, process data is only gathered for the most important processes in an LCA. Together, these are called the so-called **foreground system**. The foreground system is typically shown in flowcharts. For less important or more standardised processes (that form the **background system**), existing databases are used. For example, when a process uses one kWh of electricity from the national grid, a default process from a database can be used to include all emissions and extractions related to the use of one kWh of grid electricity. The use of background data therefore (greatly) simplifies the data gathering, as not every LCA needs to gather data on the emissions of (for example) the entire national electricity mix. The background databases (e.g. Ecoinvent) are available through specialised LCA software (such as SimaPro).