Life Cycle Assessment of Chemical Recycling for Food Grade Film

On behalf of The Consumer Goods Forum

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List of Acronyms

ADP	Abiotic Depletion Potential
AP	Acidification Potential
APC	Air Pollution Control
CFF	Circular Footprint formula
CGF	Consumer Goods Forum
CR	Chemical Recycling
CML	Centre of Environmental Science at Leiden
EF	Environmental Footprint
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
HFO	Heavy fuel oil
HVR	Heavy vacuum residue
ILCD	International Cycle Data System
JRC	Joint Research Center of the European Commission
ISO	International Organization for Standardization
kg	kilogram (metric unit of mass)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Polyethylene – low density
LHV	Lower heating value
MJ	Mega Joule (unit of energy)
MR	Mechanical Recycling
MRF	Material recovery facility
MSWI	Municipal solid waste incineration
MPW	Mixed plastic waste
n/a	not applicable
NMVOC	Non-Methane Volatile Organic Compound
PEF	Product Environmental Footprint
PE-HD	Polyethylene – high density
POCP	Photochemical Ozone Creation Potential

PP	Polypropylene
PS	Polystyrene
t	tonne (metric unit of mass)
transp.	transported
UBA	Umweltbundesamt (German Environmental Agency)
VOC	Volatile Organic Compound

Glossary

Life Cycle

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

Life Cycle Assessment (LCA)

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

Life Cycle Inventory (LCI)

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

Life Cycle Impact Assessment (LCIA)

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

Life Cycle Interpretation

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

Functional Unit

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

Allocation

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

Closed-loop and Open-loop Allocation of Recycled Material

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

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

(ISO 14044:2006, section 4.3.4.3.3)

Foreground System

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

Background System

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

Critical Review

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

Executive Summary

The Consumer Goods Forum (CGF) is a not-for-profit association that brings together the CEOs and senior management of retailers, manufacturers, service providers, and other stakeholders globally. The CGF is a platform for collaboration between retailers and manufacturers to drive innovation and tackle global challenges within the consumer goods industry.

Sphera was commissioned by the Consumer Goods Forum to conduct a life cycle assessment (LCA) on pyrolysis and related chemical recycling technologies (Py-CR) of post-consumer mixed plastic waste (MPW). The goal is to evaluate the potential environmental impacts of circular, chemically recycled (CR) food grade plastics-to-plastics (P2P) systems compared to conventional, fossil-based ones.

Ultimately, this study aims to provide additional information to help practitioners and decision makers better understand the impact of scaling such technology for 'hard-to-recycle' flexibles as a complementary solution to existing mechanical recycling.

For a comprehensive life cycle assessment of CR and equivalent comparative product systems, the study combines both the product and waste perspective of the Py-CR.

The study covers the plastic-to-plastic value chain starting from mixed plastic waste (MPW) to the end-of-life (EoL) of Py-CR compared to the current and commonly used cradle-to-grave product systems with primary production and incumbent waste treatment options of incineration with energy recovery and landfill.

The function of both product systems is the production of virgin-grade, food-grade film and the EoL treatment of the mixed plastic waste (MPW). The fossil-based product system is expanded to encompass both the food-grade film as well as the waste treatment of the mixed plastic waste that the chemical recycling product system uses as a feedstock (referred to as system expansion).

Accordingly, the functional unit (FU) is defined as

> **1 tonne[1] of food grade film (equal mix of polyethylene /polypropylene) produced and the corresponding amount of 1.26 tonne[2] mixed plastic waste managed in Europe.**

This study uses primary data from three technology providers for the Py-CR, while secondary data was used for conventional production and waste treatment processes.

The study considers a collection rate of 85% of packaging film to achieve a 55% recycling rate for PP/PE film according to the European recycling targets in 2030 (European Parliament, 2008). The six scenarios evaluated in this study (Table ES-1) consider the production and waste treatment options; incineration (scenarios 1-4), landfill (scenario 5), and a mixed EoL scenario with 55% landfill and 45% incineration (scenario 6).

The product systems are assessed with the current electricity grid (scenarios 1-2) and the 2030 electricity grid mixes (scenarios 3-6) to evaluate the Py-CR in the context of a further decarbonised electricity mix in Europe. To evaluate the relevant parameters for the Py-CR, the scenarios include current (scenario 1 and 3) and 5% higher yields (scenario 2 and 4) for the Py-CR process.

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[1] In this study, 1 tonne refers to the amount of food grade film produced. 1 tonne refers to metric tonne, the unit of mass equal to 1,000 kg.

[2] In this study, 1.26 tonne refers to the amount of mixed plastic waste to produce 1 tonne of food grade film. Points are used as decimal separators.

Table ES-1: Product systems compared and setup of scenarios of the study

	Incineration								*Landfill*		*Inc/Land*	
	Scenario 1		*Scenario 2*		*Scenario 3*		*Scenario 4*		*Scenario 5*		*Scenario 6*	
	A1	*B1*	*A2*	*B2*	*A3*	*B3*	*A4*	*B4*	*A5*	*B5*	*A6*	*B6*
Feedstock	CR - pyrolysis oil	Virgin fossil naphtha	CR - pyrolysis oil **better yield**	Virgin fossil naphtha	CR - pyrolysis oil	Virgin fossil naphtha	CR - pyrolysis oil **better yield**	Virgin fossil naphtha	CR - pyrolysis oil	Virgin fossil naphtha	CR - pyrolysis oil	Virgin fossil naphtha
End of Life (EoL)	CR	**100% Incineration**	CR	**100% Incineration**	CR	**100% Incineration**	CR	**100% Incineration**	CR	**100% Landfill**	CR	**55 % Landfill, 45% Incineration (EU rate)**
Energy grid mix	Current		Current		2030		2030		2030		2030	
System expansion	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from landfill**	N/A	**MPW diverted from landfill & incineration**

- Product system A: Pyrolysis and related chemical recycling technologies (Py-CR)
- Product system B: Fossil-based (conventional system)

The key findings of the study for the selected impact categories; climate change and fossil resource use are as follows:

- Regarding climate change (Figure ES-1-1), the Py-CR pathway has lower total GWP than the primary naphtha production with 100% incineration (B1 to B4) and mixed EoL (B6). The product systems with EoL incineration and mixed EoL are mainly driven by combustion emissions during waste incineration resulting in higher total GWP results compared to the Py-CR product systems. Due to the waste incineration impacts, the Py-CR product systems also perform better, if credits for EoL materials and energy recovery were disregarded due to a cut-off approach.

  The total GWP impact of the Py-CR product system is higher compared to the product system with landfilling at EoL (B5). Among all EoL options, landfilling benefits from negligible GHG emissions for waste treatment. The 100% landfilling scenario for the naphtha-based product system has the lowest total GWP impact; however, it also results in the worst option for fossil resource depletion as neither material nor energy are recovered from the managed waste.

  The contribution analysis shows that the highest contributions to overall GWP results of the comparator systems (B1 to B4) are mainly caused by carbon dioxide emissions during waste incineration, followed by combustion emissions during steam cracking. For the Py-CR product system, the highest contributions to total GWP results occur during steam cracking and associated combustion emissions. This is followed by combustion emissions caused by process gas to produce heat in the Py-CR process.

- The fossil resource use results (Figure ES-1-2) show the main advantage of the circular Py-CR product system over a linear virgin naphtha-based product system. The Py-CR process outperforms all comparative product systems assessed due to the mixed plastic waste used as a feedstock for food grade film production.

  The highest total fossil resource depletion potential occurs for primary naphtha production with landfilling in EoL (B5) as neither material nor energy is recovered from the landfilled material. This shows the impacts of a linear product system based on primary, fossil-based raw material production and waste treatment without any recycling activity. The 100% landfilling scenario (B5) for the naphtha-based product system results in the lowest result for climate change, but is the worst option for fossil resource depletion.

  The contribution analysis shows that the highest contributions of the comparative systems (B1 to B6) are due to the naphtha production from crude oil as the main driver. As the fossil content of the raw material for Py-CR process is sourced from burden-free mixed plastic waste, the natural gas consumption during steam cracking is the main contributor to overall fossil resource use for the Py-CR product system.

- Higher yields of the Py-CR process (A2 and A4) result in slightly lower total GWP results for the Py-CR product system.
- Given a future electricity grid mix based on higher amounts of renewable energy sources results in higher impacts for the incineration-based product systems (B3 and B4) due to decreased credits for energy recovery and thus, potential advantages of the Py-CR product system are likely to increase with further technological development and further decarbonisation of the electricity grid mix.

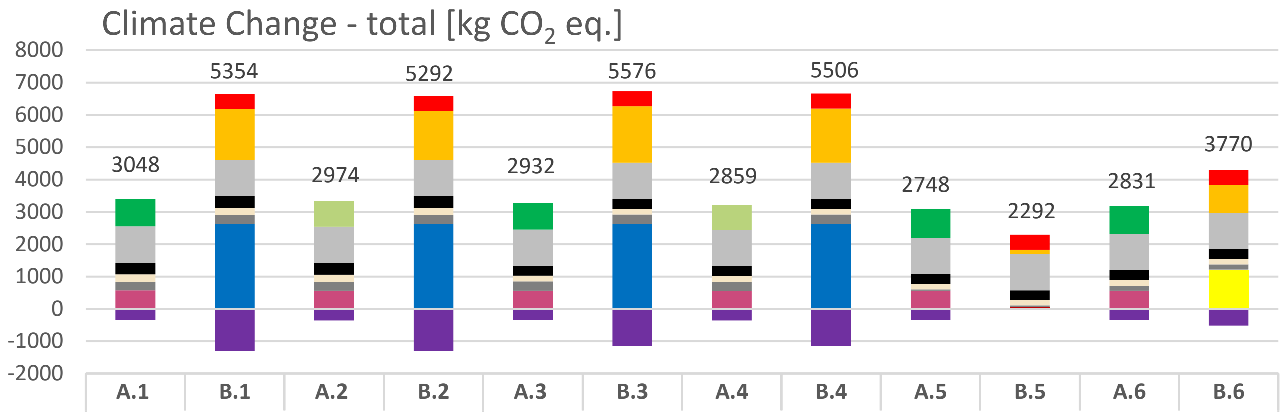
Additional scenario analyses further showed the following:

- The life cycle results of the incineration-based product system are sensitive to assumptions of electricity credits given for electricity grid mix substitutes. Although the relative ranking between the product systems remains the same with electricity from coal or natural gas, the difference becomes marginal regarding climate change based on electricity substitutes from coal. The share of fossil energy sources to be substituted by plastic waste incineration has a large influence on the overall impacts of the incineration-based product systems. The higher the share of fossil energy sources in electricity generation, the more likely it is that the GWP of the Py-CR product system is on par with or better than the incineration-based product systems.
- Life cycle impact results of the Py-CR product system are sensitive to the EoL collection rate of 85%; however, the relative ranking between the product systems compared remains in most cases given a higher collection rate of 100% or a lower collection rate of 30%. The environmental performance of the Py-CR using plastic waste as feedstock is dependent on technological developments and assumptions of mixed plastic streams and collection efficiencies.

In summary, the plastic-to-plastic Py-CR product system shows lower impacts in climate change and fossil resource usage compared to current cradle-to-grave product systems based on primary process data for the Py-CR and assumptions on the substituted combustion emissions of energy generation.

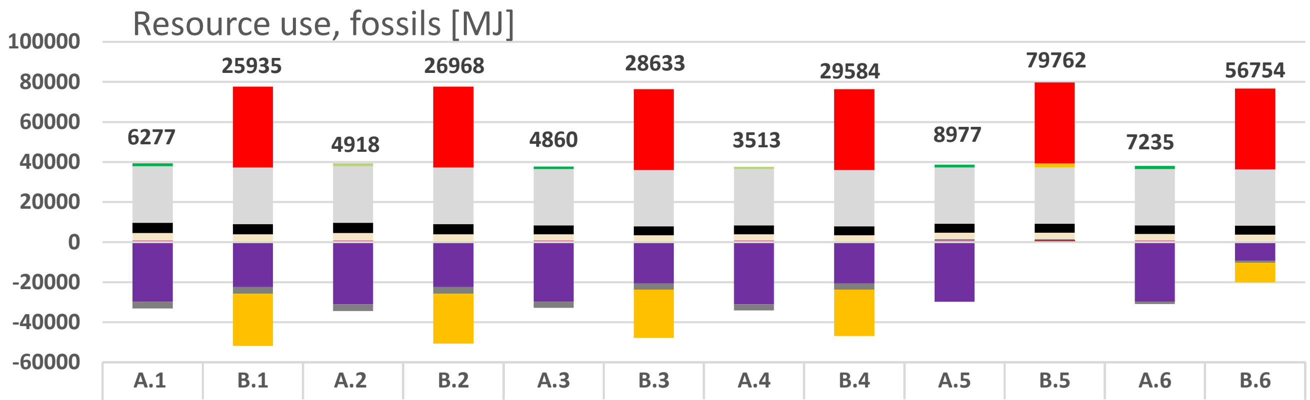
The pyrolysis-based chemical recycling technology (Py-CR) investigated in this study is capable of reducing the amount of mixed plastic waste (MPW) sent to incineration and landfilling and enabling a high-quality recycling of a low-quality waste stream that is otherwise not suitable for mechanical recycling. While these two benefits are fully aligned with the goals of a circular economy, this life cycle assessment study aimed to establish the environmental impact categories of climate change and fossil resource use of the plastic-to-plastic Py-CR product system compared to a more 'linear' way of producing food-grade PE and PP film using a data-driven and science-based approach. In addition, the study was able to highlight specific hotspots and trade-offs associated with each impact category analysed.

To stay up-to-date and get more accurate scenarios, Py-CR data should be updated as newer data becomes available. The largest need for data collection of the pyrolysis technology and related chemical recycling technologies, upstream and downstream processes include yields, product properties, quality requirements, collection and sorting rates and efficiencies.



	A.1	B.1	A.2	B.2	A.3	B.3	A.4	B.4	A.5	B.5	A.6	B.6
	Current electricity mix				2030 electricity mix							
🟩 Pyrolysis oil	841				823				897		864	
🟩 Pyrolysis oil, 5% higher yield			792				775					
🟥 Naphtha		465		465		465		465		465		465
🟧 System expansion (waste collection, sorting, EoL treatment)		1577		1514		1745		1676		133		858
■ Steam cracking	1124	1124	1124	1124	1120	1120	1120	1120	1120	1120	1120	1120
■ Polymerisation	364	364	364	364	304	304	304	304	304	304	304	304
■ Film Extrusion	222	222	222	222	178	178	178	178	170	170	173	173
■ EoL Waste collection & sorting	270	270	270	270	290	290	290	290	41	41	153	153
■ EoL chemical recycling	570		559		560		549		560		560	
🟦 EoL incineration		2631		2631		2631		2631				
🟥 EoL landfill										60		
🟨 EoL landfill & incineration												1217
🟪 EoL Credits (material and energy substitutes)	-343	-1298	-357	-1298	-343	-1157	-357	-1157	-343	0	-343	-521
Total	3048	5354	2974	5292	2932	5576	2859	5506	2748	2292	2831	3770
Reduction / Increase of CR scenario over benchmark	-43%		-44%		-47%		-48%		+20%		-25%	

Figure ES-1-1: Global warming potential per tonne of food grade film and 1.26 tonne of mixed plastic waste managed



	A.1	B.1	A.2	B.2	A.3	B.3	A.4	B.4	A.5	B.5	A.6	B.6
	Current electricity mix				2030 electricity mix							
🟩 Pyrolysis oil	1528				1312				1558		1558	
🟩 Pyrolysis oil, 5% higher yield			1452				1246					
🟥 Naphtha		40467		40467		40467		40467		40467		40467
🟧 System expansion (waste collection, sorting, EoL treatment)		-26026		-24994		-23975		-23024		2040		-9667
⬜ Steam cracking	28145	28145	28145	28145	28096	28096	28096	28096	28096	28096	28096	28096
⬛ Polymerisation	5132	5132	5132	5132	4392	4392	4392	4392	4392	4392	4392	4392
⬜ Film Extrusion	3638	3638	3638	3638	3106	3106	3106	3106	3228	3228	3173	3173
⬛ EoL Waste collection & sorting	-3328	-3328	-3328	-3328	-3088	-3088	-3088	-3088	661	661	-1026	-1026
🟥 EoL chemical recycling	952		941		832		822		832		832	
🟦 EoL incineration		321		321		321		321				
🟥 EoL landfill										877		
🟨 EoL landfill & incineration												627
🟪 EoL Credits (material and energy substitutes)	-29790	-22414	-31062	-22414	-29790	-20687	-31062	-20687	-29790	0	-29790	-9309
Total	6277	25935	4918	26968	4860	28633	3513	29584	8977	79762	7235	56754
Reduction / Increase of CR scenario over benchmark	-76%		-82%		-83%		-88%		-89%		-87%	

Figure ES-1-2: Fossil resource use per tonne of food grade film and 1.26 tonne of mixed plastic waste managed

1. Introduction

1.1. A circular economy for plastics

In 2019, the global production of plastics accounted for 368 million tonnes, with approximately 51% of plastics produced in Asia. In Europe, about 57.9 million tonnes of plastics were produced in 2019, which corresponds to approximately 16% of global production. With about 40% share of the plastics demand in Europe, packaging represents the largest end-use market (PlasticsEurope, 2020).

The current life cycle of plastics covers the transformation of fossil based raw materials into plastic products via various converting technologies, such as injection moulding or extrusion. At the EoL of plastics, the post-consumer plastic waste typically consists of mixed plastics contaminated by organic and inorganic fractions.

Currently, the EoL treatment of post-consumer waste plastic includes mechanical recycling, energy recovery and landfilling. In 2018, 29.1 million tonnes of plastic waste were collected in Europe, of which about 42.6% was incinerated to recover the embodied energy in plastics in the form of heat, approximately 32.5% was mechanically recycled, and about 24.9% was sent to landfill (PlasticsEurope, 2020).

Avoidance, reduction and reuse are the most favourable options regarding plastic waste management according to the European waste hierarchy, followed by recycling, energy recovery and landfill. Circular economy and reduction of plastic waste are high priorities for the European Union, resulting in stricter legislation, extended producer responsibility (EPR) and specific recycling targets (Ragaert, et al., 2017).

1.2. The role of chemical recycling

In recycling, new raw materials are produced via mechanical or chemical pathways, which are described in the following.

1.2.1. Overview of chemical recycling methods

Potential benefits include recycling and waste treatment of heterogeneous of plastic waste fractions where mechanical separation is not feasible (Ragaert, et al., 2017).

According to ISO 15270 (2008), chemical recycling (also known as “feedstock recycling”) is defined as *“conversion of monomers or production of new raw materials by changing the chemical structure of plastic waste through cracking, gasification or depolymerization, excluding energy recovery and incineration.”* Thermal and chemical processes are used to breakdown plastic waste into its hydrocarbon constituents.

Depending on the CR technology, different outputs are produced:

- *Depolymerization* is a reverse polymerization reaction which transforms mono-material waste plastic (e.g., PET bottles) into monomers, which can be re-polymerized into new products.
- *Gasification* converts mixed plastic waste into syngas, a gaseous mixture of hydrogen and carbon monoxide which can be used to build larger building blocks for new chemicals.
- *Pyrolysis* converts mixed plastics into pyrolysis oil in an inert atmosphere, which can be cracked down and further refined for new plastics production.

1.2.2. Pyrolysis technology

The pyrolysis and related thermal technologies assessed in the study shows one of the highest technology maturity levels among the CR technologies being developed (Solis & Silveira, 2020). This report combines the data from three technology providers, of which two are “conventional” pyrolysis technologies, and one is Hydrothermal Upgrading (HTU), a patented technology.

- **Pyrolysis technology** converts plastics into basic chemicals by thermal decomposition at elevated temperatures over >500 °C. This study focuses on the CR technology pyrolysis with the feedstock “mixed plastic waste” (MPW) and the resulting product is “refined pyrolysis oil”, which can be cracked down and further refined for new plastics production of virgin feedstock quality.
- **Hydrothermal Upgrading or Hydrothermal Liquefaction** combines the process characteristics of pyrolysis (high heat) and solvolysis (dissolution) to heat, melt and then dissolve in steam the mixed plastics feedstocks at so-called supercritical conditions to crack plastics back to the liquid hydrocarbons, the building blocks from which it was originally made. HTU operates at a lower overall temperature than “conventional” pyrolysis. The efficiency of heat transfer and ability to control reaction conditions avoids charring and generating other unwanted reaction by-products (technological process description shared by the company providing primary data for this LCA study). Please refer to Annex A: Hydrothermal Upgrading for further information.

CR products based on the pyrolysis technology have similar characteristics to petrochemical feedstocks and plastics that would usually be produced using virgin fossil feedstocks. These products are considered to have the potential to substitute virgin fossil feedstocks, thus reducing dependency on finite resources. However, to achieve the virgin grade quality, an additional plastic feedstock sorting step is required to remove any non-target plastic and other materials (glass, paper, metals), and so maximise process yield and quality.

1.2.3. Limits of mechanical recycling

Current material recycling is primarily mechanical recycling. It includes the following processing steps: collection, separation, shredding, washing and extrusion into secondary plastic granulates. The mechanical recycling of mixed polymers produces polymer blends consisting of a mixture of two or more polymers.

As post-consumer plastic waste consists of mixed plastics with various contaminants, the separation and subsequent processing required for mechanical recycling is technically and economically challenging (Rickert et al., 2020; Davidson et al., 2021).

Mechanical recycling systems can recycle some post-consumer flexible plastic packaging, but the recycled outputs from this process generally have fewer applications, lower value, and cannot be used in food-grade packaging. As the number of re-processing cycles in mechanical recycling increases, it degrades the polymer that is being recycled (Solis & Silveira, 2020). The recycled material degrades in mechanical properties (e.g., tensile strength) resulting in downcycled material that is often more expensive than virgin plastic (Ragaert, et al., 2017; Solis & Silveira, 2020) due to re-processing steps. Many plastic waste streams cannot be completely separated before recycling; thus, the final recycled product contains a mix of different types of plastic, which affects the physical properties of the recycled polymer and reduces the field of potential applications of the recycled plastic. Major proportions of flexible and multi-layer plastic packaging are therefore not suitable for mechanical recycling (Rickert, et al., 2020).

Accordingly, mechanical recycling of suitable waste plastic streams is preferred to pyrolysis-based CR due to its lower energy demand and lower costs, but it has some limitations:

- Challenges in producing food grade PP and PE[3] and other higher quality recycled content grades (e.g. natural/ivory) to meet growing market demand;
- Losses in material properties and a build-up of additives and other contaminants, limiting recycling loops before quality deteriorates;

In the face of these challenges, pyrolysis can be considered as a complementary technology to produce food-grade recycled PE and PP packaging from materials that are not processed through mechanical recycling today.

1.3. Goal of the study

Sphera was commissioned by the Consumer Goods Forum (CGF) to conduct an LCA on pyrolysis and related chemical recycling technologies (Py-CR) of post-consumer mixed plastic waste (MPW) to evaluate the potential environmental impacts regarding climate change and fossil resource use of circular food grade plastics-to-plastics (P2P) systems compared to linear, fossil-based ones.

The intended application of this study is to provide life cycle-based results of potential environmental impacts (climate change and fossil resource use) associated with Py-CR in the context of plastic waste treatment and plastic production. Food-grade plastic film is chosen as the representative plastic application since this type of plastic packaging is most likely to not be recycled mechanically. For the purposes of this study, polyethylene and polypropylene are used as the main polymer components of such films.

The plastic-to-plastic Py-CR product system scenario is compared to a conventional 'linear' system where virgin fossil raw materials are used to make plastic and different EoL options are used to process the waste (predominantly energy recovery). To explore under what conditions the Py-CR product system outperforms the comparative system, different scenarios with different assumptions are explored. The intended audience of the study is CGF members, internal and external stakeholders of the CGF, and interested public in Europe regarding waste management, plastic waste treatment and circular economy in the chemical industry.

The results are intended to support comparative footprint statements and intended to be disclosed to the public. The study has been conducted according to the requirements of 14044 (ISO 14044, 2006). The study has been critically reviewed by a panel of three independent experts in accordance with ISO 14044, clause 6.3.

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[3] Apart from mechanical recycling of rigid HDPE (e.g. milk jugs) into food-grade rHDPE in some markets

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product Systems, Product Functions, Functional Unit and System Boundary

For a comprehensive LCA of the Py-CR product system and equivalent comparative product systems, the study combines the product and waste perspective by assessing the plastic-to-plastic impact pathway of the Py-CR production route. In the product perspective, the Py-CR is considered as alternative option to produce virgin grade plastic. In the waste perspective, the Py-CR is considered an alternative waste treatment option to incinerate with energy recovery and/or landfill for mixed plastic waste currently not mechanically recycled.

The study covers the plastic-to-plastic Py-CR product chain from mixed plastic waste (MPW) to end-of-life versus current cradle-to-grave product systems with primary production and incumbent waste treatment options, incineration with energy recovery and landfill.

The function of the product system is the production of virgin-grade food grade film and the respective treatment of mixed plastic waste (MPW).

The functional unit (FU) is defined as:

> **1 tonne[4] of food grade film (equal mix of polyethylene /polypropylene) produced and the corresponding amount of 1.26 tonne[5] mixed plastic waste managed in Europe.**

For the scenarios 2 and 4, the Py-CR product systems are considered with a 5% higher yield and the functional unit corresponds to:

> **1 tonne of food grade film (equal mix of polyethylene /polypropylene) produced and the corresponding amount of 1.21[6] tonne of mixed plastic waste managed[7] in Europe.**

The reference flow is the same as the functional unit. The function and functional unit are consistent with the defined goal of the study.

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[4] In this study, 1 tonne refers to the amount of food grade film produced. 1 tonne refers to metric tonne, the unit of mass equal to 1,000 kg.

[5] In this study, 1.26 tonne refers to the amount of mixed plastic waste to produce 1 tonne of food grade film. Points are used as decimal separators.

The system boundaries of the Py-CR product system and the comparative cradle-to-grave-system with the different end-of-life (EoL) options are provided in Table 2-1, in Figure 2-1 (incineration), Figure 2-2 (landfill), and Figure 2-3 (mixed end-of-life treatment).

Two selected resource input production technologies are assessed:

- Py-CR including pre-processing of the mixed plastic waste through extra sorting and post processing of the pyrolysis oil through hydrotreatment, using mixed plastic waste to produce chemically recycled pyrolysis oil as naphtha substitute
- Conventional production of primary naphtha from crude oil

Both product systems include the same subsequent film production technologies with steam cracker, polymerization, and film extrusion. The steam cracker uses either the chemically recycled pyrolysis oil or virgin fossil naphtha as feedstock. As the chemically recycled pyrolysis oil after hydrotreatment provides the same virgin grade quality as primary naphtha, both output products are considered as equivalent precursor for the steam cracker without any quality losses.

The Py-CR technology is based on primary data collected based on process design modelling data from three pyrolysis and related technologies pilot plants in Europe for 2020. The upstream and downstream processes, e.g., waste collection and film production, are based on secondary data from the GaBi database and literature.

The conventional naphtha production and the film production technologies are based on secondary data from the GaBi database representing industrial averages in Europe. The study considers the European average composition of fossil naphtha and natural gas (proxy for natural gas liquids) used as feedstock for the steam cracker.

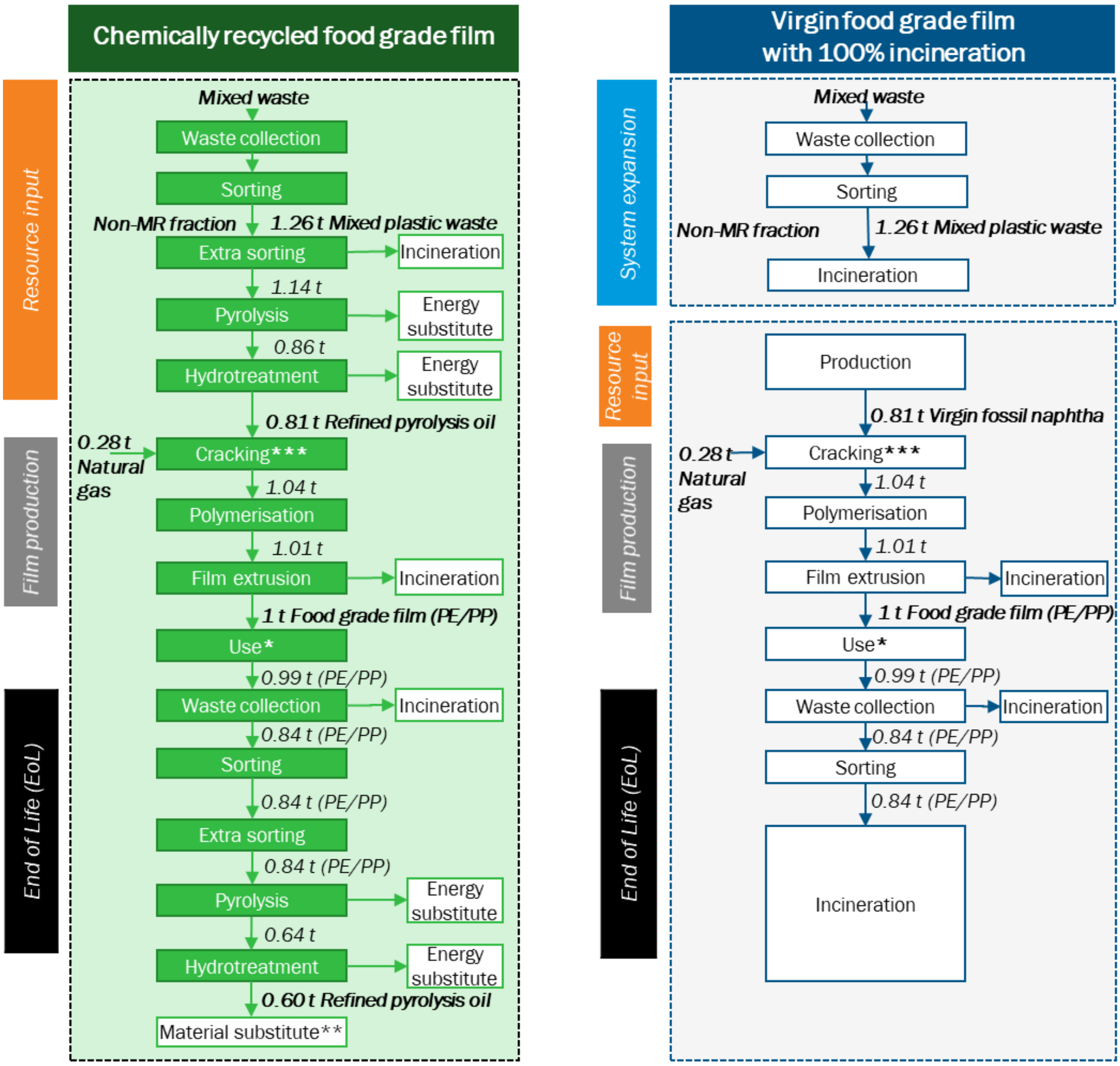
The yields from the Py-CR stages, hydrotreating, cracking, and polymerization phases determine how much mixed plastic waste is needed to manufacture 1 tonne of PE/PP. the current demand per tonne of PE/PP is 1.26 tonne of mixed plastic waste and 0.28 tonne of natural gas (proxy for natural gas liquids). For further information of the steam cracker inputs and natural gas dataset, please see section 3.2.6.

Three end-of-life treatment technologies are assessed:

- Py-CR, including pre-processing of extra sorting and post processing of hydrotreatment, using mixed plastic waste to produce chemically recycled pyrolysis oil as naphtha substitute
- Conventional treatment of mixed plastic waste
    - Polypropylene (PP) / Polyethylene (PE) in waste incineration plant
    - Plastic waste on landfill

The study focuses on the environmental life cycle impacts of food grade film in a waste management system that includes Py-CR as an end-of-life option for plastics currently, compared to the impacts of virgin plastic in today’s waste management system.

The comparative product systems include system expansions due to multifunctionality of Py-CR. The Py-CR process fulfils two functions – waste management and production. System expansion was applied to enable a fair comparison between the plastic-to-plastic Py-CR product systems and the status quo of cradle-to-grave product systems.



* Use phase and distribution not included within the scope. Losses to the environment included

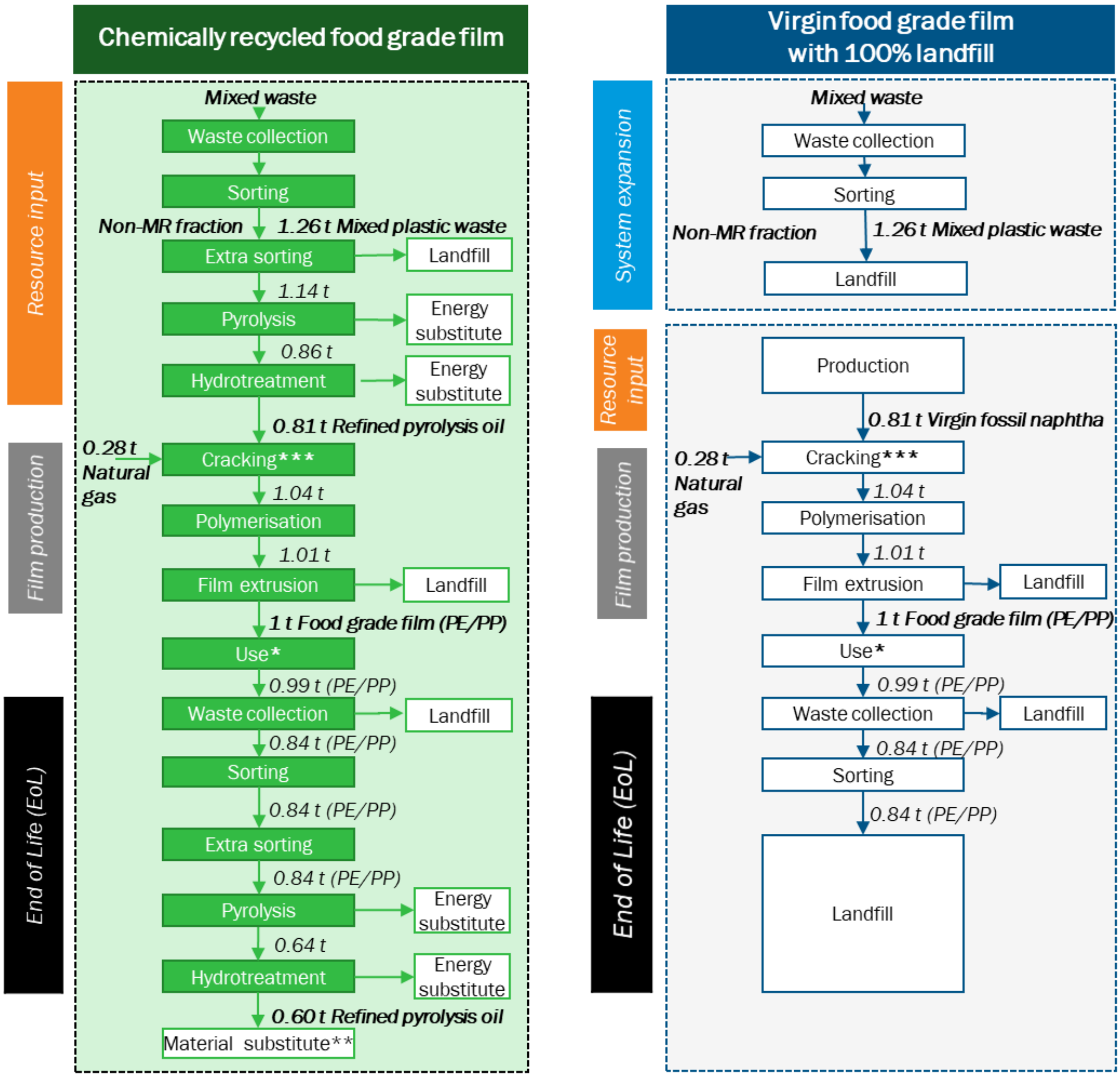
** Virgin fossil naphtha

***Please refer to section 3.2.6 for further details on mass balance and efficiency at the steam cracker

Figure 2-1: Product system of packaging film based on chemically recycled pyrolysis oil versus primary naphtha production and end-of-life incineration

The product systems assessed represent production and waste treatment options currently available based on primary data available for the Py-CR technology and industry-average data in Europe. However, the scenarios established for this study do not represent current waste treatment systems all over Europe as plastic films are not collected in the same manner in the recyclables waste streams in many European countries.

The compared product systems focus on post-consumer mixed plastic waste streams rejected by material recovery facilities (MRF). The post-consumer waste collection system for packaging film is assumed based on the recycling targets of 55% in Europe in 2030 as being enforced by the Directive (EU) 2018/852 (European Parliament, 2018). The packaging films are collected and transported to MRF where they are sorted and combined into one stream consisting of rejected polymers from multiple sources. For the Py-CR product system, the rejected waste stream passes through an additional sorting step to create a suitable input stream for the Py-CR processing. For the comparative scenarios, the rejected waste stream is managed according to the EoL option assessed, such as 100% incineration, 100% landfill and mixed EoL treatment of 55% incineration and 45% landfill.



* Use phase and distribution not included within the scope. Losses to the environment included

** Virgin fossil naphtha

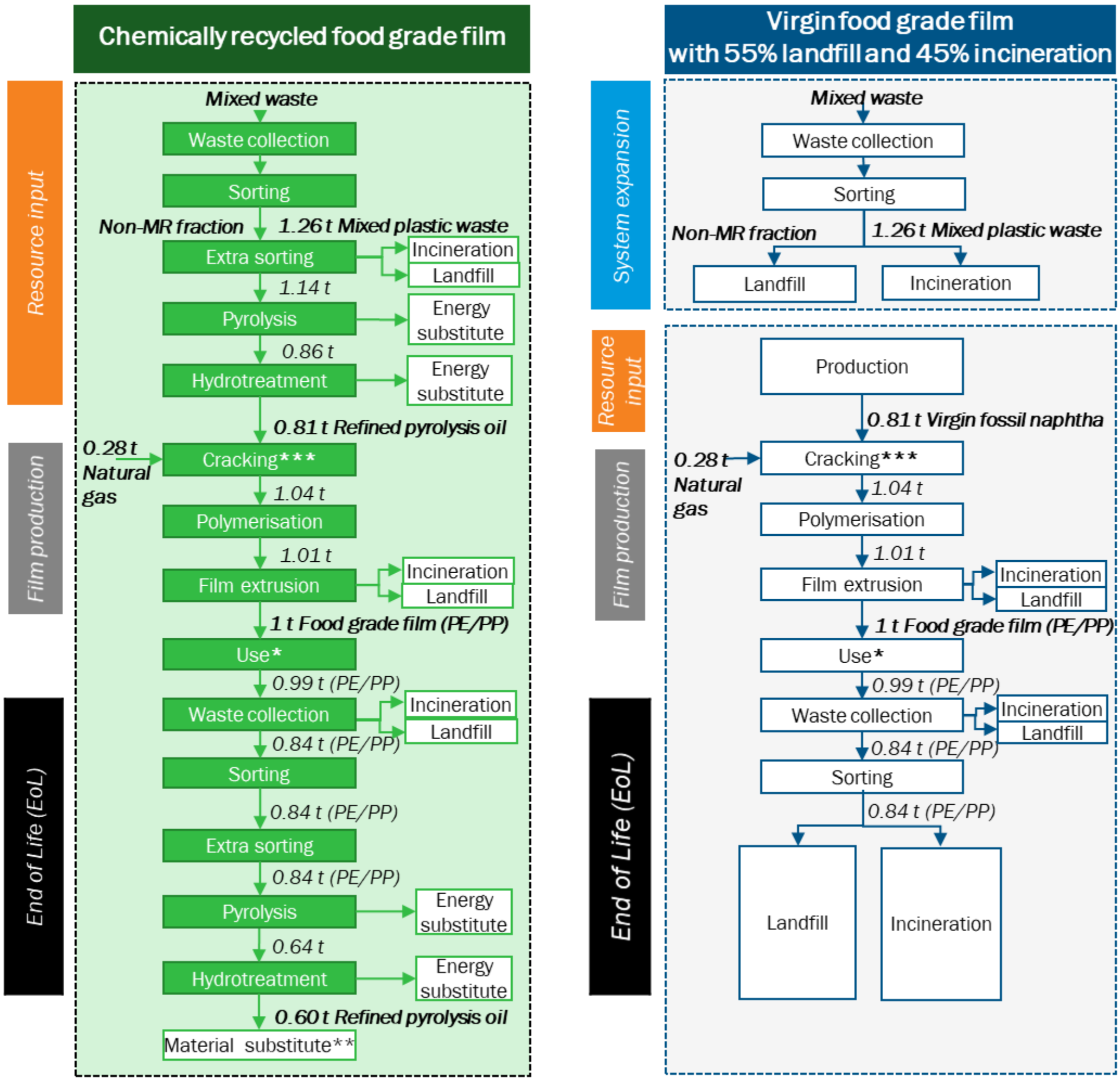
***Please refer to section 3.2.6 for further details on mass balance and efficiency at the steam cracker

Figure 2-2: Product system of packaging film based on chemically recycled pyrolysis oil versus primary naphtha production and end-of-life landfill

Losses along the life cycle, such as manufacturing waste during film extrusion, packaging films etc. that are not captured during waste collection and rejected inputs for the Py-CR during the additional sorting are assumed to be managed according to the EoL option assessed.

In summary, the following scenarios are assessed in the study:

- **Scenario 1**: Chemically recycled food grade film (A.1) versus virgin food grade film and waste treatment with 100% incineration (B.1) with current electricity grid mix for both product systems



** Use phase and distribution not included within the scope. Losses to the environment included*
*** Virgin fossil naphtha*
****Please refer to section 3.2.6 for further details on mass balance and efficiency at the steam cracker*

Figure 2-3: Product system of packaging film based on chemically recycled pyrolysis oil versus primary naphtha production and mixed end-of-life landfill and incineration

- Scenario 2: Chemically recycled food grade film with a 5%[8] higher yield (A.2) versus virgin food grade film and waste treatment with 100% incineration (B.2) with current electricity grid mix for both product systems
- Scenario 3: Chemically recycled food grade film (A.3) versus future virgin food grade film and waste treatment with 100% incineration (A.4) with 2030 electricity grid mix for both product systems

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[8] As the chemical recycling system is considered with a 5% higher yield, the amount of plastic waste managed is 5% lower, see also functional unit as defined for scenario 2.

- **Scenario 4:** Chemically recycled food grade film with a 5% higher yield (A.4) versus future virgin food grade film and waste treatment with 100% incineration (A.4) with 2030 electricity grid mix[9] for both product systems
- **Scenario 5:** Chemically recycled food grade film (A.5) versus future virgin food grade film and waste treatment with 100% landfill (B.5) with 2030 electricity grid mix for both product systems
- **Scenario 6:** Chemically recycled food grade film (A.6) versus future virgin food grade film and waste treatment with 55% landfill and 45% incineration (B.6) with 2030 electricity grid mix for both product systems

The six scenarios evaluated in this study (Table 2-1) consider the production and waste treatment options incineration (scenarios 1-4), landfill (scenario 5), and a mixed EoL scenario with 55% landfill and 45% incineration (scenario 6). The study considers a collection rate of 85%[10] of packaging film to achieve a 55% recycling rate for PP/PE film according to the European recycling targets in 2030 (European Parliament, 2008).

The product systems are assessed with current electricity grid (scenarios 1&2) and 2030 electricity grid mixes (scenarios 3 through scenario 6) to evaluate the Py-CR technology in the context of a further decarbonised electricity mix in Europe. To evaluate the relevant parameters for the Py-CR technology, the scenarios include current (scenario 1 and 3) and 5% higher yields (scenario 2 and 4) for the Py-CR processing step.

As emerging technologies will be optimized over the next ten years, a higher production efficiency with a 5% higher yield for the Py-CR technology is assumed in scenario 2. Scenario 3 reflects a future electricity grid mix for both product systems for the year 2030, and scenario 4 combines the future electricity mix and a 5% higher yield for the pyrolysis oil. As the conventional production and waste treatment technologies mature, increased production efficiencies are not applied. A summary of the scenarios and compared product systems is provided in Table 2-1.

Table 2-1: Product systems compared and setup of scenarios of the study

	Incineration								*Landfill*		*Inc/Land*	
	Scenario 1		*Scenario 2*		*Scenario 3*		*Scenario 4*		*Scenario 5*		*Scenario 6*	
	A1	***B1***	***A2***	***B2***	***A3***	***B3***	***A4***	***B4***	***A5***	***B5***	***A6***	***B6***
Feedstock	CR - pyrolysis oil	Virgin fossil naphtha	CR - pyrolysis oil **better yield**	Virgin fossil naphtha	CR - pyrolysis oil	Virgin fossil naphtha	CR - pyrolysis oil **better yield**	Virgin fossil naphtha	CR - pyrolysis oil	Virgin fossil naphtha	CR - pyrolysis oil	Virgin fossil naphtha
End of Life (EoL)	CR	**100% Incineration**	CR	**100% Incineration**	CR	**100% Incineration**	CR	**100% Incineration**	CR	**100% Landfill**	CR	**55 % Landfill, 45% Incineration (EU rate)**
Energy grid mix	Current		Current		2030		2030		2030		2030	
System expansion	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from incineration**	N/A	**MPW diverted from landfill**	N/A	**MPW diverted from landfill & incineration**

- Product system A: Pyrolysis and related chemical recycling technologies (Py-CR)
- Product system B: Fossil-based (conventional system)

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[9] As the chemical recycling system is considered with a 5% higher yield, the amount of plastic waste managed is 5% lower, see also functional unit as defined for scenario 4.

[10] Mixed plastic waste (MPW) collected ≈ 85% ≈ $\frac{0{,}55 \times 1{,}14\, t\, MPW \times (0{,}81\, t\, refined\ \ pyrolysis\ oil + 0{,}28\, t\, natural\ gas)}{1\, t\, plastic\ film \times 0{,}81\, t\, refined\ pyrolysis\ oil}$

Table 2-2 provides a summary of the system boundaries of the product systems evaluated.

Table 2-2: System boundaries

Included	Excluded
✓ Conventional naphtha production ✓ Processing of naphtha and refined pyrolysis oil to plastic film ✓ Mixed waste collection and transport to sorting plant ✓ Mixed waste sorting ✓ EoL Py-CR for plastic-to-plastic route ✓ EoL landfilling and/or incineration of conventional film	× Use phase and distribution × EoL reprocessing of standard mechanical recycling fraction × EoL Py-CR for plastics-to-fuel route × Capital goods, infrastructure, and employee commute

The current available mechanical recycling technology is considered out of scope for this study as the study assesses the mixed plastic diverted from multiple sources, including polymer fractions that are not suitable for mechanical recycling.

The study considers the Py-CR impact pathway for plastic-to-plastic only. Other potential plastic-to-fuel products based on Py-CR are not within the scope. Production of capital equipment and infrastructure are excluded as these are not relevant when allocated to the film production output from the production line. The use phase is not considered in the scope of the study; however, losses to the environment were included without any treatment. Consumer use is excluded as impacts are the same for all product systems investigated and thus, are not expected to be dependent on production and EoL options assessed.

2.2. Technology coverage

The intended technology references cover the following production and end-of-life treatments for food grade film:

- Collection and sorting of mixed plastic post-consumer waste
- Additional sorting of the mixed plastic waste fraction used as feedstock for Py-CR
- Conventional pyrolysis based on thermal cracking and pyrolysis based on water-based thermal cracking process (hydrocracking) including downstream hydrotreatment to produce chemically recycled pyrolysis oil as naphtha substitute as well as EoL treatment of mixed plastic waste
- Production of primary fossil naphtha used as a feedstock for the steam cracker
- Steam cracking, polymerization and film extrusion based on naphtha and pyrolysis oil feedstock
- Waste incineration technology with energy recovery for polyethylene and polypropylene and plastic waste landfill

As the Py-CR technology is not fully implemented at industrial scale, the results from the assessment of the technologies are considered as intermediate results.

2.3. Time coverage

To assess baseline scenarios, the time reference is the year of 2020; whereas for future waste management options the reference year is 2030.

The future scenarios cover:

- The generation of electricity based on the electricity grid mix in 2030
- Collection rate of 85% according to European recycling targets of 55% for plastic in 2030
- Production efficiency of the Py-CR process with a 5% higher yield

The 5% increase in the yield for the Py-CR process is based on current primary data and represents an estimated increase in production efficiency for the emerging Py-CR technology for the future scenarios. Results are intended to be valid until significant technological developments occur and new data is available.

While an increase in production efficiency of the emerging Py-CR technology is considered in scenario 2 and 4, the comparator systems represent mature technologies already optimised, and major technical improvements are not expected until 2030. Thus, the current data for the comparative production and end-of-life technologies are applied for the future scenarios in 2030.

2.4. Geographical Coverage

The intended geographical reference is Europe.

2.5. Allocation

2.5.1. Multi-output Allocation

Multi-output allocation generally follows the requirements of ISO 14044, section 4.3.4.2. When allocation becomes necessary during the data collection phase, the allocation rule most suitable for the respective process step is applied and documented along with the process in Chapter 3.

Allocation of background data (energy and materials) taken from the GaBi 2021 databases is documented online (Sphera Solutions Inc., 2021).

2.5.2. End-of-Life Allocation

End-of-Life allocation generally follows the requirements of ISO 14044, section 4.3.4.3. Such allocation approaches address the question of how to assign impacts from virgin production processes to material that is recycled and used in future product systems.

Substitution approach (also known as 0:100, closed-loop approximation, recyclability substitution or end-of-life approach) – this approach is based on the perspective that material that is recycled into secondary material at end-of-life will substitute an equivalent amount of virgin material. Hence a credit is given to account for this material substitution. However, this also means that burdens equivalent to this credit should be assigned to scrap used as an input to the production process, with the overall result that the impact of recycled granulate is the same as the impact of virgin material. This approach rewards end-of-life recycling but does not reward the use of recycled content.

In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas. The latter represents the cleanest fossil fuel and therefore results in a conservative estimate of the benefits of energy recovery.

In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilisation rates (flaring vs. power production). A credit is assigned for power output using the regional grid mix.

Value-corrected substitution – this variation of the substitution approach enables the inclusion of further considerations, such as changes of inherent properties (e.g., due to downcycling) or differences between market values of primary and secondary materials. Upstream burdens are allocated to scrap inputs and market average recycling credits are given based on the value of the recycled material compared to the primary raw material. This approach enables to consider a quality correction without any upstream burden for waste in the production phase.

2.6. Cut-off Criteria

No cut-off criteria are defined for this study. As summarized in section 2.1, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The choice of proxy data is documented in Chapter 3. The influence of these proxy data on the results of the assessment has been carefully analysed and is discussed in Chapter 5.

2.7. Selection of LCIA Methodology and Impact Categories

This study assesses LCIA results based on selected indicators of the Environmental Footprint (EF) 3.0[11]. The analysis, discussion and interpretation of the study results focusses on the following selection of indicators:

- Climate Change (GWP)
- Resource use (energy carriers)

Justification for the selection of relevant impact categories:

- Climate change is of high public interest and considered to be the most pressing environmental issue with far-reaching impacts in the twenty-first century.
- Depletion of energy resources was considered to account for the material and energy recovery from plastic waste replaces the need for fossil feedstocks.
- Further impact categories recommended in the EF 3.0 set of indicators were not considered. The list includes ozone depletion potential (no ozone-depletion emissions in the foreground systems), ionising radiation, resource use of minerals and metals (not internationally accepted), ecotoxicity, land use and water use (high uncertainty due to lowest recommendation level III (Fazio, 2018) for the impact assessment method to be applied with caution). The impact categories of acidification potential, eutrophication potential and photochemical ozone formation were initially included in the scope of the study. However, due to methodological questions posed by the chemical recycling technology owners concerning the incineration of plastic packaging waste that could not be resolved within the time

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[11] The Environmental Footprint reference packages are periodically reviewed and updated by the European Commission, available at http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

period of the study, those impact categories were excluded from the scope to allow the publication of climate change and fossil resource use results. Future iterations of the study should try to resolve the issue in order to address a more complete set of impact categories. Respiratory inorganics was excluded as it was considered out of the scope of the study.

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-3.

The Environmental Footprint indicators were originally based on the ILCD recommended methods (Hauschild, 2011), but several have since been modified and updated by the European Commission as part of the ongoing development of the Product Environmental Footprint initiative. EF 3.0 characterisation factors are considered the most robust and up-to-date available for the European context, are widely used and respected within the LCA community, and are required for Product Environmental Footprint studies and Environmental Product Declarations under EN 15804+A2.

The global warming potential impact category is assessed based on the current IPCC characterisation factors taken from the 5th Assessment Report (IPCC, 2013) for a 100-year timeframe (GWP100) as this is currently the most commonly used metric[12]. It should be noted that there is no scientific justification for selecting this over other available timeframes.

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures the fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

Table 2-3: Impact category descriptions

Impact Category	Description	Unit	Reference
Climate change (global warming potential)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect.	kg CO_2 equivalent	(IPCC, 2013)
Resource use, energy carriers	A measure of the total amount of non-renewable primary energy extracted from the earth. Resource use is expressed in energy demand from non-renewable resources including both fossil sources (e.g., petroleum, natural gas, etc.) and uranium for nuclear fuel. Efficiencies in energy conversion (e.g., power, heat, steam, etc.) are taken into account.	MJ	(Guinée et al., 2002; van Oers et al., 2002)

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[12] The climate change methodology used in EF 3.0 is based on the latest IPCC reports but also includes the effects of "climate-carbon feedback" which results in higher global warming potentials but is also associated with greater uncertainty. In this study we have used the more commonly-applied emission factors from the same report that exclude climate-carbon feedback effects.

This LCA study does not apply normalisation to establish the order of magnitude in which each product system would contribute to the average environmental burden of a given year.

As this study intends to support comparative footprint statements to be disclosed to third parties, no grouping or further quantitative cross-category weighting has been applied. Instead, each impact is discussed in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

2.8. Interpretation to be Used

The results of the LCI and LCIA were interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions and limitations

Note that in situations where no product outperforms all of its alternatives in each of the impact categories (climate change and fossil resource use), some form of cross-category evaluation is necessary to draw conclusions regarding the environmental superiority of one product over the other.

2.9. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study’s goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in Chapter 5 of this report.

2.10. Type and Format of the Report

In accordance with the ISO requirements (ISO, 2006) this document aims to report the results and conclusions of the LCA completely, accurately and without bias to the intended audience. The results, data, methods, assumptions, and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.11. Software and Database

The LCA model was created using the GaBi 10.0.1 Software system for life cycle engineering, developed by Sphera Solutions Inc. The GaBi 2021 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.12. Critical Review

A panel review according to ISO 14044, section 6.3, was conducted with the following panel members:

- Dr. Jennifer Dunn, Associate Professor, Chemical and Biological Engineering, Northwestern University, US
- Simon Hann, Principal Consultant, Eunomia Research & Consulting Ltd., UK
- Dr. Llorenç Milà i Canals, Programme Officer, United Nations Environment Programme, France

The review was conducted in accordance with ISO/TS 14071. The Critical Review Statement can be found in Annex C: Critical Review Statement. The Critical Review Report containing the comments and recommendations by the independent experts as well as the practitioner’s responses is available upon request from the study commissioner in accordance with ISO/TS 14071.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

Primary data were collected using customised data collection templates, which were sent out by email to the respective data providers in the participating companies. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, Sphera engaged with the data provider to resolve any open issues. The data provided by the Py-CR companies included: raw materials / pre-cursors, water use, auxiliaries, electricity consumption, steam and thermal energy, products, waste for recovery, incineration, and/or landfill, water output, emissions to water and direct process emissions to air.

Wherever feasible, the coefficient of variation was established for the different inputs and outputs, either across different data providers or across the reported time period if a breakdown into smaller increments (e.g., 12 months) was available.

Secondary data from GaBi was used in the foreground system of the model, GaBi databases uses are given throughout the report document. Documentation for all GaBi datasets can be found online (Sphera, 2021).

The data collected can be summarized as follows:

- Primary data from three pyrolysis companies and related technologies.
- Secondary data from literature and GaBi 2021 database for waste collection, sorting, hydrotreatment, steam cracker, polymerisation, film production, and end-of-life scenarios; incineration and landfill. Please see section 3.2 for further details.
- Primary data from one pyrolysis company and secondary data from literature for the extra sorting process
- Secondary data from GaBi 2021 database for all background data. Please see section 3.4 for further information.

3.2. Product systems A - Chemical recycling product systems

Figure 2-1 to Figure 2-3 provide an overview of the Py-CR product systems per tonne of food grade film produced and managed at the EoL. The unit processes assessed for the Py-CR product system are described in the following subsections.

3.2.1. Waste collection

Mixed waste is collected and transported from the point of generation (households) to the sorting plant and then to the extra-sorting plant. The mixed plastic waste is considered with a value correction without any upstream virgin material burden.

An average collection distance of 55 km by truck was derived from literature (Kaitinnis, 2019). This distance was equally distributed across four different bulk waste trucks available in the GaBi databases (Table 3-1). Empty return load during collection and transportation of mixed waste is also considered.

Table 3-1: Transport parameters for waste collection

Distance	Unit	DQI*	Source	Mode
55	km	Literature	(Kaitinnis, 2019)	Bulk waste truck, Euro 6, 20 - 26t gross weight / 10t payload capacity (urban area) Bulk waste truck, Euro 6, 20 - 26t gross weight / 10t payload capacity (rural area) Bulk waste truck, Euro 5, 20 - 26t gross weight / 10t payload capacity (rural area) Bulk waste truck, Euro 5, 20 - 26t gross weight / 10t payload capacity (urban area)

* measured / calculated / estimated / literature

3.2.2. Sorting

At the sorting plant, the waste is sorted into three main waste groups: single plastic waste streams (polyethylene (PE), polypropylene (PP), polystyrene and polyethylene terephthalate), mixed plastic waste, and residual mixed waste fractions (tinplate, aluminium, paper, cardboard, beverage cartons, etc.).

Economic allocation was applied in the background system to distribute the environmental burdens between co-products in proportion to the market prices of the waste products after sorting as shown in Table 3-2.

The data of recovered waste fractions and prices were derived from (Kaitinnis, 2019). Based on economic allocation of energy between the waste fractions, approximately 19.5% of environmental impacts are allocated to the mixed plastic waste (MPW) as the target feedstock. Further consideration of other waste output flows is not within the scope in the foreground system.

Table 3-2: Parameters for the sorting process

Parameters	Value	Unit	DQI*	Source
Mixed plastic waste fraction	110	€/t	Literature	(Kaitinnis, 2019)
Single plastic waste stream	228	€/t	Literature	(Kaitinnis, 2019)
Residual waste fractions	0	€/t	Literature	(Kaitinnis, 2019)
Electricity	250	MJ per tonne MPW	Literature	(Kaitinnis, 2019)

* measured / calculated / estimated / literature

Table 3-3 shows the input and output flows of the sorting process after economic allocation to the target waste fraction ‘mixed plastic waste’ and their respective amounts considered per tonne of food grade film.

Table 3-3: Sorting process per tonne of PE/PP food grade film (after economic allocation)

Type	Flow	Value	Unit	DQI*	Source
Inputs	Electricity	314.6	MJ	Literature	(Jeswani et al., 2021)
	Mixed plastic waste	1258.5	kg	Literature	(Jeswani et al., 2021)
Outputs	Mixed plastic waste	1258.5	kg	Literature	(Jeswani et al., 2021)

* measured / calculated / estimated / literature

3.2.3. Extra sorting

To enable mixed plastic waste as suitable feedstock for further Py-CR processing and, to improve its calorific value, an additional sorting is performed. The additional sorting step enables the targeted high-calorific mixed plastic waste to be separated from residual waste.

The target MPW fraction consists of lightweight packaging materials, such as polyethylene, polypropylene and polystyrene (DerGrünePunkt, 2018). The study assumes a calorific value for the targeted MPW of 44 MJ/kg according to the average net calorific values of PE and PP.

Table 3-4 shows the modelling assumptions for the electricity consumption and sorting efficiency derived from literature (Jeswani, et al., 2021) and chemical providers.

Table 3-4: Parameters for the extra sorting process

Parameters	Value	Unit	DQI*	Source
Electricity	331.5	MJ per tonne MPW	Calculated	(Jeswani, et al., 2021); Chemical providers
Sorting efficiency	90	%	Calculated	(Jeswani, et al., 2021); Chemical providers

* measured / calculated / estimated / literature

The remaining waste and impurities from extra sorting step resulting in packaging waste losses are considered according to the EoL options assessed for the comparative systems in each scenario: 100% incineration with energy recovery, 100% landfill, or a mixed EoL with 55% landfill and 45% incineration. Arising inert waste and hazardous waste during extra sorting is assumed to be landfilled based on (Russ et al., 2020).

The additional sorting process with the quantities required for the Py-CR processing during production is shown in Table 3 5.

Table 3-5: Extra sorting process per tonne of PE/PP food grade film during production

Type	Flow	Value	Unit	DQI*	Source
Inputs	Mixed plastic waste collected	1258.5	kg	Literature	(Jeswani, et al., 2021)
	Electricity	378.2	MJ	Literature	(Jeswani, et al., 2021)
Outputs	Mixed plastic waste	1140.8	kg	Literature	(Jeswani, et al., 2021)
	Packaging waste loss	118.3	kg	Literature	(Jeswani, et al., 2021)
	Glass/inert waste to landfill	8.0	kg	Literature	(Russ, et al., 2020)
	Hazardous waste to landfill	1.6	kg	Literature	(Russ, et al., 2020)

* measured / calculated / estimated / literature

3.2.4. Pyrolysis oil

In Py-CR process, the mixed plastic waste is heated in the absence of oxygen to decompose polymers into rich saturated hydrocarbon vapours. The condensable gases are converted to pyrolysis oil by atmospheric distillation. The non-condensable gases are combusted to provide energy for the process. The emissions from this combustion are accounted for in this study. The Py-CR step includes scrubbers and selective catalytic reduction in the Py-CR plant to limit air emissions.

Data for the Py-CR process, such as process yields, energy use, waste and emissions were derived from two pyrolysis companies using traditional thermal cracking process and one company using a water-based thermal cracking process in Europe. This report is based on the average data provided by three technology providers. To maintain confidentiality of the data and given that the number of data sets is only three, no numerical and statistical information can be disclosed regarding the spread of the data. However, from a qualitative point of view the data provided was within a reasonable range which does not materially change the overall results of the study. As such, if each of those data sets was used independently, the overarching conclusions of the LCA analysis would still be directionally valid for all the scenarios.

Table 3-6 shows the average inventory of the Py-CR process based on primary data from process modelling data for pilot plants. Allocation of co-products was applied based on their net calorific value.

Table 3-6: Py-CR process per tonne of PE/PP food grade film during production

Type	Flow	Value	Unit	DQI*	Source
Inputs	Mixed plastic waste	1140.8	kg	Calculated	Chemical providers
	Methanol	0.1	kg	Calculated	Chemical providers
	Carbamide	3.5	kg	Calculated	Chemical providers
	Sodium hydroxide	2.8	kg	Calculated	Chemical providers
	Sulphuric acid	2.8	kg	Calculated	Chemical providers
	Water (desalinated; deionised)	1146.8	kg	Calculated	Chemical providers
	Water (tap water)	28	kg	Calculated	Chemical providers
	Electricity	1108.2	MJ	Calculated	Chemical providers
	Thermal energy	130	MJ	Calculated	Chemical providers
	Synthetic gas from pyrolysis	166.6	kg	Calculated	Chemical providers
Outputs	Pyrolysis oil	862.3	kg	Calculated	Chemical providers
	Synthetic gas for internal combustion	166.6	kg	Calculated	Chemical providers
	Electricity	21.9	MJ	Calculated	Chemical providers
	Waste for landfill	45.6	kg	Calculated	Chemical providers
	Wastewater - untreated	882.4	kg	Calculated	Chemical providers
	Hazardous waste (unspec.)	1.3	kg	Calculated	Chemical providers
	Oxygen	1165.7	kg	Calculated	Chemical providers
	Water vapour	410.3	kg	Calculated	Chemical providers
	Carbon dioxide	411.9	kg	Calculated	Chemical providers
	Nitrogen oxides	0.5	kg	Calculated	Chemical providers
	Nitrogen	0.3	kg	Calculated	Chemical providers
	Ammonia	2.02E-02	kg	Calculated	Chemical providers
	Carbon monoxide	5.50E-02	kg	Calculated	Chemical providers
	Sulphur dioxide	3.68E-03	kg	Calculated	Chemical providers
	Hydrogen chloride	5.11E-03	kg	Calculated	Chemical providers
	Dust	2.41E-03	kg	Calculated	Chemical providers
	Total organic carbon	1.89E-03	kg	Calculated	Chemical providers
	Heavy metals to air	2.43E-05	kg	Calculated	Chemical providers
	Hydrogen fluoride	2.70E-05	kg	Calculated	Chemical providers
	Thallium	6.49E-08	kg	Calculated	Chemical providers
	Cadmium	6.49E-08	kg	Calculated	Chemical providers
	Mercury	2.73E-08	kg	Calculated	Chemical providers
	Polychlorinated dibenzo-p-dioxins	1.35E-09	kg	Calculated	Chemical providers
	Polychlorinated dibenzo-p-furans	1.35E-09	kg	Calculated	Chemical providers

* measured / calculated / estimated / literature

3.2.5. Hydrotreatment

During hydrotreatment process, the pyrolysis oil is purified and hydrogenated to be suitable for manufacturing virgin grade plastic. An average efficiency of 94% was applied based on two literature sources (Zero Waste Scotland, 2013; Bezergianni, et al., 2017). The residues created during this process are used internally as thermal energy for hydrotreatment. The net calorific value of residues (42,5 MJ/kg) is calculated based on the net calorific value of crude pyrolysis oil, as derived from (Zero Waste Scotland, 2013).

Table 3-7: Hydrotreatment process per tonne of PE/PP food grade film during production

Type	Flow	Value	Unit	DQI*	Source
Inputs	Pyrolysis oil (unrefined)	862.3	kg	Literature	(Zero Waste Scotland, 2013)
	Hydrogen	8.6	kg	Literature	(Zero Waste Scotland, 2013)
	Thermal energy	496.8	MJ	Literature	(Zero Waste Scotland, 2013)
Outputs	Pyrolysis oil (refined)	810.5	kg	Literature	(Zero Waste Scotland, 2013; Bezergianni, et al., 2017)
	Residues for internal combustion	51.7	kg	Literature	(Zero Waste Scotland, 2013)

* measured / calculated / estimated / literature

3.2.6. Steam cracker

Purified pyrolysis oil and natural gas are used as feedstock in a steam cracker to produce ethylene and propylene, which then are polymerised. Allocation by net calorific value is applied for co-products of the steam cracker. The co-products considered in the GaBi model are described as follows; hydrogen, pyrolysis gas, refinery gas, BTX-fraction, and butadiene mix.

The inventory data for the production of ethylene and propylene from pyrolysis oil are shown in Table 3-8 and Table 3-9. These datasets represent the average inventory in Europe derived from the GaBi database covering higher (88%) and lower (78%) efficiencies for the steam cracker processing to address variations between site-specific productions sites. The efficiencies of the steam cracker are calculated based on energy balance. Figure 3-1 provides a graphical representation of the overall inputs and outputs of the ethylene steam cracker according to the data summarised in Table 3-8 and after applying energy allocation by net calorific value for co-products. For the water and air emissions, please refer to Table 3-8.

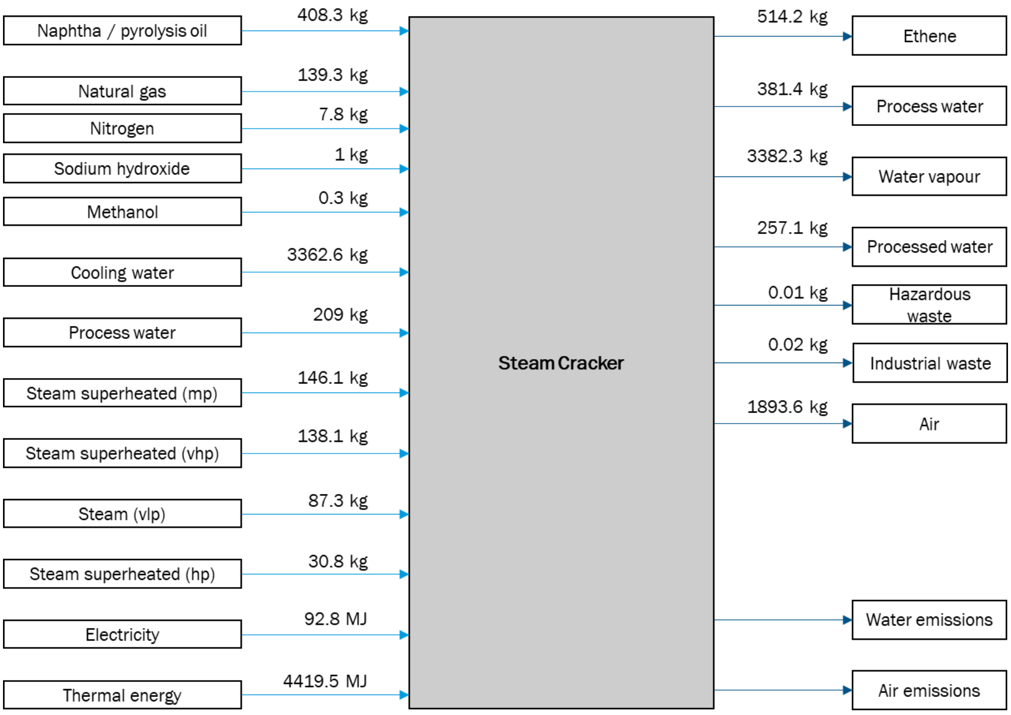

Figure 3-1: Ethylene steam cracker

For further information on the steam cracker dataset to produce ethylene, please refer to http://gabi-documentation-2021.gabi-software.com/xml-data/processes/45e41797-e9a1-4ee9-af29-75ae71d1943f.xml

For further information on the steam cracker dataset to produce propylene, please refer to http://gabi-documentation-2021.gabi-software.com/xml-data/processes/ec09778b-711d-4078-8a9a-6cd37c4a4176.xml

Details of GaBi's steam cracker model are considered intellectual property and cannot be published in a publicly accessible report. This document provides as much detail as possible and it is recognized that, given it must exclude many details, the results of this study may not be replicable without access to the GaBi software.

The cracker input material naphtha is replaced by refined pyrolysis oil on a weight-by-weight basis assuming the same net calorific value of 44 MJ/kg for both refined pyrolysis oil and naphtha. The assumption is based on the net calorific values of the pyrolysis oil shared by the technology providers, for which an average value of 43 MJ/kg was obtained.

The natural gas dataset covers the entire supply chain of natural gas and represents the European consumption mix including domestic production and imports. This includes well drilling, natural gas production and processing as well as transportation via pipeline and LNG tanker. Main technologies such as conventional (primary, secondary, tertiary) and unconventional production (shale gas, tight gas, coal bed methane), both including parameters like energy consumption, transport distances, gas processing technologies are individually considered for each production country. All-natural gas delivering countries, including domestic production, contribute their corresponding shares taken from national statistics to the European natural gas mix. The inventory is mainly based on secondary data.

For further information on the natural gas data set applied, please refer to http://gabi-documentation-2021.gabi-software.com/xml-data/processes/c6387e19-933f-4726-a7ad-7a8050aa418c.xml

Table 3-8: Ethylene steam cracking per tonne of PE/PP food grade film (allocated by net calorific value)

Type	Flow	Value	Unit	DQI*	Source
Inputs	Pyrolysis oil (refined)	408.3	kg	Literature	GaBi database 2021
	Natural gas. at consumer EU-28	139.3	kg	Literature	GaBi database 2021
	Nitrogen gaseous	7.8	kg	Literature	GaBi database 2021
	Sodium hydroxide (50%; caustic soda)	1	kg	Literature	GaBi database 2021
	Methanol	0.3	kg	Literature	GaBi database 2021
	Water (cooling water)	3362.6	kg	Literature	GaBi database 2021
	Water (process water)	209	kg	Literature	GaBi database 2021
	Steam superheated (mp)	146.1	kg	Literature	GaBi database 2021
	Steam superheated (vhp)	138.1	kg	Literature	GaBi database 2021
	Steam (vlp)	87.3	kg	Literature	GaBi database 2021
	Steam superheated (hp)	30.8	kg	Literature	GaBi database 2021
	Electricity	92.8	MJ	Literature	GaBi database 2021
	Thermal energy (from feedstock)	4419.5	MJ	Literature	GaBi database 2021
Outputs	Ethene (ethylene)	514.2	kg	Literature	GaBi database 2021
	Water (process water)	381.4	kg	Literature	GaBi database 2021
	Industrial waste for municipal disposal	0.02	kg	Literature	GaBi database 2021
	Hazardous waste (unspec.)	0.01	kg	Literature	GaBi database 2021
	Water vapour	3382.3	kg	Literature	GaBi database 2021
	Used air	1893.6	kg	Literature	GaBi database 2021
	Processed water to river	257.1	kg	Literature	GaBi database 2021
	Ammonium / ammonia	1.60E-02	kg	Literature	GaBi database 2021
	Cadmium. heavy metals to air	3.48E-09	kg	Literature	GaBi database 2021
	Chemical oxygen demand (COD)	6.39E-02	kg	Literature	GaBi database 2021
	Chromium. heavy metals to air	1.13E-06	kg	Literature	GaBi database 2021
	Copper. heavy metals to air	2.44E-08	kg	Literature	GaBi database 2021

Type	Flow	Value	Unit	DQI*	Source
	Cyanide. inorganic emissions to fresh water	5.23E-04	kg	Literature	GaBi database 2021
	Dust (PM2.5)	5.23E-04	kg	Literature	GaBi database 2021
	Hydrocarbons (unspecified)	3.83E-03	kg	Literature	GaBi database 2021
	Lead. heavy metals to air	1.05E-09	kg	Literature	GaBi database 2021
	Lead. heavy metals to fresh water	5.57E-05	kg	Literature	GaBi database 2021
	Mercury. heavy metals to air	5.23E-10	kg	Literature	GaBi database 2021
	Mercury heavy metals to fresh water	3.14E-07	kg	Literature	GaBi database 2021
	Nickel. heavy metals to air	1.22E-07	kg	Literature	GaBi database 2021
	Nickel. heavy metals to fresh water	5.92E-04	kg	Literature	GaBi database 2021
	NMVOC (unspecified)	2.61E-01	kg	Literature	GaBi database 2021
	Phenol. hydrocarbons to fresh water	5.40E-04	kg	Literature	GaBi database 2021
	Vanadium	4.01E-08	kg	Literature	GaBi database 2021
	Zinc. heavy metals to fresh water	3.66E-05	kg	Literature	GaBi database 2021
	Zinc. heavy metals to air	6.97E-08	kg	Literature	GaBi database 2021

* measured / calculated / estimated / literature

Table 3-9: Propylene steam cracking per tonne of PE/PP food grade film (allocated by net calorific value)

Type	Flow	Value	Unit	DQI*	Source
Inputs	Pyrolysis oil (refined)	402.2	kg	Literature	GaBi database 2021
	Natural gas. at consumer EU-27	137.2	kg	Literature	GaBi database 2021
	Nitrogen gaseous	7.7	kg	Literature	GaBi database 2021
	Sodium hydroxide (50%; caustic soda)	1	kg	Literature	GaBi database 2021
	Methanol	0.3	kg	Literature	GaBi database 2021
	Water (cooling water)	3312.3	kg	Literature	GaBi database 2021
	Water (process water)	205.9	kg	Literature	GaBi database 2021
	Steam superheated (mp)	143.9	kg	Literature	GaBi database 2021
	Steam superheated (vhp)	136.1	kg	Literature	GaBi database 2021
	Steam (vlp)	86	kg	Literature	GaBi database 2021
	Steam superheated (hp)	30.3	kg	Literature	GaBi database 2021
	Electricity	91.4	MJ	Literature	GaBi database 2021
	Thermal energy (from feedstock)	4353.3	MJ	Literature	GaBi database 2021
Outputs	Propene (propylene)	521.8	kg	Literature	GaBi database 2021
	Water (process water)	375.7	kg	Literature	GaBi database 2021
	Industrial waste for municipal disposal	0.02	kg	Literature	GaBi database 2021
	Hazardous waste (unspec.)	0.01	kg	Literature	GaBi database 2021
	Water vapour	3331.7	kg	Literature	GaBi database 2021
	Used air	1865.3	kg	Literature	GaBi database 2021
	Processed water to river	253.2	kg	Literature	GaBi database 2021
	Ammonium / ammonia	1.58E-02	kg	Literature	GaBi database 2021
	Cadmium. heavy metals to air	3.43E-09	kg	Literature	GaBi database 2021
	Chemical oxygen demand (COD)	6.30E-02	kg	Literature	GaBi database 2021
	Chromium. heavy metals to air	1.12E-06	kg	Literature	GaBi database 2021
	Copper. heavy metals to air	2.40E-08	kg	Literature	GaBi database 2021
	Cyanide. inorganic emissions to fresh water	5.15E-04	kg	Literature	GaBi database 2021
	Dust (PM2.5)	5.15E-04	kg	Literature	GaBi database 2021
	Hydrocarbons (unspecified)	3.78E-03	kg	Literature	GaBi database 2021
	Lead. heavy metals to air	1.03E-09	kg	Literature	GaBi database 2021
	Lead. heavy metals to fresh water	5.49E-05	kg	Literature	GaBi database 2021
	Mercury. heavy metals to air	5.15E-10	kg	Literature	GaBi database 2021

Type	Flow	Value	Unit	DQI*	Source
	Mercury heavy metals to fresh water	3.09E-07	kg	Literature	GaBi database 2021
	Nickel. heavy metals to air	1.20E-07	kg	Literature	GaBi database 2021
	Nickel. heavy metals to fresh water	5.84E-04	kg	Literature	GaBi database 2021
	NMVOC (unspecified)	2.57E-01	kg	Literature	GaBi database 2021
	Phenol. hydrocarbons to fresh water	5.32E-04	kg	Literature	GaBi database 2021
	Vanadium. heavy metals to air	3.95E-08	kg	Literature	GaBi database 2021
	Zinc. heavy metals to fresh water	3.60E-05	kg	Literature	GaBi database 2021
	Zinc. heavy metals to air	6.86E-08	kg	Literature	GaBi database 2021

* measured / calculated / estimated / literature

3.2.7. Polymerisation

The input and output flows of the polymerisation process of polyethylene and polypropylene are shown in Table 3-10 and Table 3-11, respectively. Secondary data for the polymerisation process was derived from the GaBi database representing industry average data for the technology assessed (Sphera, 2021).

For more information on the polymerisation process data set used, please refer to http://gabi-documentation-2021.gabi-software.com/xml-data/processes/df6a564c-f46e-4325-9689-022bbfe009db.xml

Table 3-10: Polyethylene low density granulate (LDPE) per tonne of PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Ethene (ethylene)	514.3	kg	Literature	GaBi DB 2021
	Nitrogen gaseous	1	kg	Literature	GaBi DB 2021
	Initiator	2.52E-02	kg	Literature	GaBi DB 2021
	Electricity	1633.5	MJ	Literature	GaBi DB 2021
	Water (process water)	403.3	kg	Literature	GaBi DB 2021
	Water (cooling water)	252.1	kg	Literature	GaBi DB 2021
	Steam (vlp)	45.4	kg	Literature	GaBi DB 2021
	Compressed air. 7 bar. average efficiency	15.1	Nm3	Literature	GaBi DB 2021
Outputs	Polyethylene low density granulate (LDPE/PE-LD)	504.2	kg	Literature	GaBi DB 2021
	Processed water to river	378.1	kg	Literature	GaBi DB 2021
	Water (process water)	40.3	kg	Literature	GaBi DB 2021
	Polyethylene (PE) waste for recovery	7.4	kg	Literature	GaBi DB 2021
	Industrial waste for municipal disposal	0.1	kg	Literature	GaBi DB 2021

* measured / calculated / estimated / literature

Table 3-11: Polypropylene granulate (PP) per tonne of PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Propene (propylene)	521.8	kg	Literature	GaBi DB 2021
	Nitrogen gaseous	22.7	kg	Literature	GaBi DB 2021
	Hydrogen	0.1	kg	Literature	GaBi DB 2021
	Catalyst	1.01E-02	kg	Literature	GaBi DB 2021
	Electricity	907.5	MJ	Literature	GaBi DB 2021
	Steam (mp)	151.3	kg	Literature	GaBi DB 2021
	Water (cooling water)	151.3	kg	Literature	GaBi DB 2021
	Compressed air. 7 bar. average efficiency	25.2	Nm3	Literature	GaBi DB 2021
Outputs	Polypropylene granulate (PP)	504.2	kg	Literature	GaBi DB 2021
	Water (process water)	143.7	kg	Literature	GaBi DB 2021
	Polypropylene (PP) waste for recovery	17.3	kg	Literature	GaBi DB 2021
	Industrial waste for municipal disposal	0.2	kg	Literature	GaBi DB 2021

* measured / calculated / estimated / literature

3.2.8. Film extrusion

The plasticized plastic granulate from the extruder is fed in the calendar. The calendar is a system of 3 or 4 counter-revolving cylinders that ensures the pressing to a unified thickness. The plastic film has a gauge of about 0.1 to 0.5 mm.

The data for the manufacturing of PE/PP film is taken from the GaBi 2021 database. For the film extrusion, a 10% scrap rate is applied derived from (EREMA, 2018) which is assumed to be used for closed loop recirculation.

Table 3-12: Film extrusion per tonne of food grade film

Type	Flow	Value**	Unit	DQI*	Source
Inputs	Plastic granulate (unspecified)	1100	kg	literature	GaBi DB 2021
	Lubricating oil	0,241	kg	literature	GaBi DB 2021
	Electricity	1760	MJ	literature	GaBi DB 2021
	Thermal energy (MJ)	220	MJ	literature	GaBi DB 2021
Outputs	PE/PP plastic film	1000	Kg	literature	GaBi DB 2021
	Plastic waste (unspecified) to for recirculation	100	Kg	literature	GaBi DB 2021; (EREMA, 2018)

* measured / calculated / estimated / literature

** Values are displayed rounded to 3 significant digits

3.2.9. Use

The use phase of the food-grade film is out of scope; however, losses of plastic to the environment during usage were estimated based on literature (Ryberg et al., 2018). The losses to the environment of 1.20% represent an estimation for the loss of plastic to the environment from mismanaged waste treatment and loss of plastic from littering. No treatment is assumed for the plastic losses to the environment.

Table 3-13: Use phase losses per tonne of food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	PE/PP plastic film	1000	Kg	estimated	(Ryberg et al., 2018)
Outputs	PE/PP plastic film to waste collection	988	Kg	estimated	(Ryberg et al., 2018)
	Losses to environment	12	Kg	estimated	(Ryberg et al., 2018)

* measured / calculated / estimated / literature

3.2.10. End-of-life

At the end-of-life, the food grade packaging film (PE/PP) is assumed to be collected and transported to the materials recovery facilities (MRFs) for waste treatment where it is sorted and diverted into an output stream consisting of rejected polymer from multiple sources.

The transport during waste collection at end-of-life is based on the same assumptions as described for waste collection during production. For a description of the transport applied, please see section 3.2.1.

At EoL, PP/PE film recycling rate is considered as 55% according to the European targets for 2030 (European Parliament, 2018), resulting in approximately 85%[13] of packaging film to be collected at end-of-life to meet the overall recycling target of 55% for all plastic. Approximately 15% of the unclaimed plastics are assumed to be treated according to the EoL treatment option assessed in each scenario, namely EoL incineration and/or EoL landfill.

Table 3-14 shows the input and output flows of the waste collection process and their respective amounts considered per tonne of food grade film during EoL waste management. For more information, please see section 3.2.1.

Table 3-14: Waste collection per tonne of PE/PP food grade film at end-of-life

Type	Flow	Value	Unit	DQI*	Source
Inputs	PE/PP plastic film to waste collection	988	kg	Estimated	(European Parliament, 2018)
Outputs	Waste collected	840	kg	Estimated	(European Parliament, 2018)
	Waste losses	148	kg	Estimated	(European Parliament, 2018)

* measured / calculated / estimated / literature

Table 3-15 shows the input and output flows of the sorting process of mixed plastic waste and their respective amounts considered per tonne of food grade film managed at EoL. For more information, please see section 3.2.2.

Table 3-15: End-of-life sorting per tonne of PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Waste collected	840	kg	Literature	(Jeswani, et al., 2021)
	Electricity for sorting	210	MJ	Literature	(Jeswani, et al., 2021)
Outputs	Waste sorted to extra sorting	840	kg	Literature	(Jeswani, et al., 2021)

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[13] Mixed plastic waste (MPW) collected ≈ 85% ≈ $\frac{0{,}55 \times 1{,}14\ t\ MPW \times (0{,}81\ t\ refined\ \ pyrolysis\ oil + 0{,}28\ t\ natural\ gas)}{1\ t\ plastic\ film \times 0{,}81\ t\ refined\ pyrolysis\ oil}$

Table 3-16 shows the input and output flows of the additional sorting process of mixed plastic waste and their respective amounts considered per tonne of food grade film managed at EoL. For a further description, please see section 3.2.3.

Table 3-16: Extra sorting process per tonne of PE/PP food grade film at end-of-life

Type	Flow	Value	Unit	DQI*	Source
Inputs	Mixed plastic waste	840	kg	Literature	(Jeswani, et al., 2021)
	Electricity	256	MJ	Literature	(Jeswani, et al., 2021)
Outputs	Mixed plastic waste	840	kg	Literature	(Jeswani, et al., 2021)

* measured / calculated / estimated / literature

The Py-CR process of mixed plastic waste is described in section 3.2.4. The Py-CR process step at EoL refers to 840 kg of MPW managed per tonne of food grade film, the relevant input and output flow amounts are scaled by a factor of 0.736.

Table 3-17 shows the input and output flows of the hydrotreatment process of pyrolysis oil and their respective amounts considered per tonne of food grade film managed at EoL. Material credits are applied for the production of primary naphtha substitutes. For a further description, please see section 3.2.5.

Table 3-17: Hydrotreatment process per tonne of food grade film managed at end-of-life

Type	Flow	Value	Unit	DQI*	Source
Inputs	Pyrolysis oil (unrefined)	634.8	kg	Literature	(Zero Waste Scotland, 2013)
	Hydrogen	6.3	kg	Literature	(Zero Waste Scotland, 2013)
	Thermal energy	366.1	MJ	Literature	(Zero Waste Scotland, 2013)
Outputs	Pyrolysis oil (refined)	596.7	kg	Literature	(Zero Waste Scotland, 2013; Bezergianni, et al., 2017)
	Residues for internal combustion	38.1	kg	Literature	(Zero Waste Scotland, 2013)

* measured / calculated / estimated / literature

3.3. Product systems B - Virgin naphtha-based product systems

Figure 2-1 to Figure 2-3 provided an overview of the comparative product systems per tonne of virgin naphtha-based PE/PP food grade film produced and managed at EoL. The processes assessed are described in the following subsections.

3.3.1. System expansion

As the Py-CR product systems fulfil two functions, i.e., waste management and material production, system expansion was applied for the comparison to alternative cradle-to-grave products systems. The system expansion covers the waste collection, sorting and waste treatment including transports of the mixed plastic waste as compared to chemically recycled pyrolysis oil and managing mixed waste at the same time. The study covers three waste treatment options: 100% incineration, 100% landfill, and a mixed end-of-life with 55% landfill and 45% incineration according to the Directive (EU) 2018/852 (European Parliament, 2018).

As system expansion is modelled according to the Py-CR product systems, the same mixed waste stream quantities and losses are considered to produce one tonne of food grade film. For a further description of the waste collection and sorting step including transports, please see section 3.2.1 and 3.2.2.

100% Incineration (scenario 1-4)

For the end-of-life incineration option (Table 3-18), secondary data from the GaBi database for polyethylene (PE) in waste incineration plant and polypropylene (PP) in waste incineration plant were used. The datasets represent the incineration of PE and PP waste in waste-to-energy plants (WtE) for the thermal treatment of municipal solid waste (MSW) in Europe with dry flue gas cleaning and selective catalytic reduction (SCR) for NOx-removal to meet the legal requirements.

Current and future electricity grid mixes (EU-28) are used for electricity credits. Thermal energy from natural gas (EU-28) is applied for thermal energy credits in current and future scenarios.

The data for waste incineration is based on the GaBi dataset that represents an average waste-to-energy plant with dry flue gas treatment, without collection, transport and pre-treatment in Europe and covers the thermal treatment of a plastic packaging waste mix with an average calorific value of 43.5 MJ/kg.

Table 3-18: Unit process data for the system expansion with 100% incineration per tonne PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Waste for incineration with energy recovery	1260	kg	Literature	GaBi DB 2021
Outputs	Thermal energy credit	12582	MJ	Literature	GaBi DB 2021
	Electricity credit	6980	MJ	Literature	GaBi DB 2021

* measured / calculated / estimated / literature

100% landfill option (scenario 5)

For the end-of-life landfill option (Table 3-19), secondary data from the GaBi database for plastic waste on landfill was used. The dataset represents a typical municipal waste landfill with surface and basic sealing meeting European limits for emissions including landfill gas treatment, leachate treatment, sludge treatment and deposition. The average dataset considers a landfill of 30 m with a landfill area of 40,000 sqm and 100 years of deposit. Sealing materials (clay, mineral coating, PE film) and diesel for the compactor are included in the data set.

Table 3-19: Unit process data for the system expansion with 100% landfill per tonne PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Plastic waste on landfill	1260	kg	Literature	GaBi DB 2021

* measured / calculated / estimated / literature

Mixed end-of-life option with 55% landfill and 45% incineration (scenario 6)

The mixed EoL scenario (Table 3-20) combines two waste treatment options with 55% landfill and 45% incineration according to the Directive (EU) 2018/852 (European Parliament, 2018).

Current and future electricity grid mixes (EU-28) are used for electricity credits. Thermal energy from natural gas (EU-28) is applied for thermal energy credits in current and future scenarios.

Table 3-20: Unit process data for the system expansion with 55% landfill and 45% incineration per tonne PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Waste for incineration with energy recovery	567	kg	Literature	(European Parliament, 2018)
	Waste for landfill	693	kg	Literature	(European Parliament, 2018)
	Waste losses				
Outputs	Thermal energy credit	5662	MJ	Literature	GaBi DB 2021
	Electricity credit	3141	MJ	Literature	GaBi DB 2021

* measured / calculated / estimated / literature

3.3.2. Steam cracker

The data for the steam cracker to produce ethylene and to produce propylene from naphtha feedstock represent average inventories derived from the GaBi database. For description of the process and data applied, please see section 3.2.6.

3.3.3. Polymerisation

For description of the process and data applied, please see section 3.2.7.

3.3.4. Film extrusion

For description of the process and data applied, please see section 3.2.8.

3.3.5. Use

For description of the process and data applied, please see section 3.2.9.

3.3.6. End-of-Life

Waste collection

For description of the process and data applied, please see section 3.2.10.

Sorting

For description of the process and data applied, please see section 3.2.10.

100% Incineration (scenario 1-4)

Quantities of input and output flows for the incineration option at EoL are provided in Table 3-21, for the landfill option are provided in Table 3-22 and for the mixed EoL option in Table 3-23. For description of the process and data applied, please see section 3.3.1.

Table 3-21: Unit process data of end-of-life incineration per tonne of PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Waste for incineration with energy recovery	840	Kg	literature	GaBi DB 2021
Outputs	Thermal energy	9977	MJ	literature	GaBi DB 2021
	Electricity	5611	MJ	literature	GaBi DB 2021

* measured / calculated / estimated / literature

100% Landfill (scenario 5)

Table 3-22: Unit process data of end-of-life landfill per tonne of PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Waste for landfill	840	kg	literature	GaBi DB 2021

* measured / calculated / estimated / literature

Mixed end-of-life with 55% Landfill and 45% (scenario 6)

Table 3-23: Unit process data of end-of-life with 55% landfill and 45% incineration per tonne of PE/PP food grade film

Type	Flow	Value	Unit	DQI*	Source
Inputs	Waste for incineration with energy recovery	378	kg	literature	GaBi DB 2021
	Waste for landfill	462	kg	literature	GaBi DB 2021
Outputs	Thermal energy	2525	MJ	literature	GaBi DB 2021
	Electricity	4490	MJ	literature	GaBi DB 2021

* measured / calculated / estimated / literature

3.4. Background System

Documentation for all GaBi datasets can be found online (Sphera Solutions Inc., 2021).

3.4.1. Fuels and Energy

Regional averages of EU-28 and EU-27, respectively, for fuel inputs and electricity grid mixes, as of 2017 and 2030, were obtained from the GaBi 2021 databases.

Table 3-24 shows the EU-28 electricity fuel mix of 2017 as considered for current electricity mix. The data set represents the average region-specific electricity supply for final consumers, including own consumption, transmission/distribution losses of electricity supply and electricity imports from neighbouring countries. Main technologies for firing, flue gas cleaning and electricity generation are considered according to the region-specific situation.

Table 3-24: EU-28 electricity grid mix (2017)

Fuel type	EU-28 - Electricity mix [%]	Source
Electricity from peat	0.2	Gabi Database 2021
Electricity from lignite	9.4	Gabi Database 2021
Electricity from hard coal	10.8	Gabi Database 2021
Electricity from coal gases	0.9	Gabi Database 2021
Electricity from natural gas	20.2	Gabi Database 2021
Electricity from fuel oil	1.8	Gabi Database 2021
Electricity from biomass (solid)	2.9	Gabi Database 2021
Electricity from biogas	2.1	Gabi Database 2021
Electricity from waste	1.5	Gabi Database 2021

Electricity from nuclear	25.3	Gabi Database 2021
Electricity from hydro	10.1	Gabi Database 2021
Electricity from wind	11.1	Gabi Database 2021
Electricity from photovoltaics	3.5	Gabi Database 2021
Electricity from solar thermal	0.2	Gabi Database 2021
Electricity from geothermal	0.2	Gabi Database 2021

The EU-27 electricity mix of 2030 covers a scenario calculated based on the “EU Reference Scenario 2016 - Energy, Transport and GHG Emissions - Trends to 2050” published by the (European Commission, 2016) with approximately 40% of renewable energy sources (Figure 3-2). It represents the average country- or region-specific electricity supply for final consumers, including electricity own consumption, transmission/distribution losses of electricity supply and electricity imports from neighbouring countries. The region-specific electricity consumption mix is provided by the conversion of the different energy carriers to electricity and imports from neighbouring countries, as illustrated in the figure below.

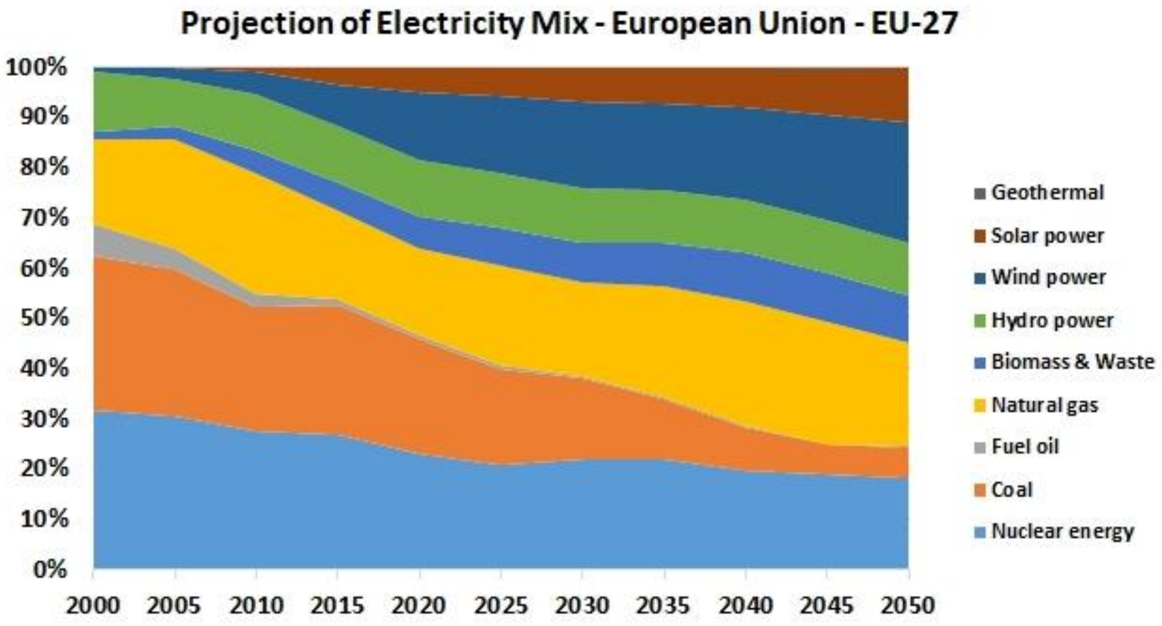

Figure 3-2: Projection of EU-27 electricity mix 2030

Table 3-25: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	EU-28	Electricity grid mix	Sphera	2017	No
Electricity	EU-27	Electricity grid mix (2030) (EU Energy trends report)	Sphera	2017	No.
Thermal energy	EU-28	Thermal energy from natural gas	Sphera	2017	No
Thermal energy	EU-28	Thermal energy from light fuel oil (LFO)	Sphera	2017	No
Steam	EU-28	Process steam from natural gas 95%	Sphera	2017	No
Natural gas	EU-28	Natural gas mix	Sphera	2017	No
Lubricants	EU-28	Lubricants at refinery	Sphera	2017	No

*Proxy legend: Geo = Geographical, Tech = Technology, Temp = Temporal

3.4.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2021 database. Table 3-26 shows the most relevant LCI datasets used in modelling the product systems.

Table 3-26: Key material and process datasets used in inventory analysis

Location	Dataset	Data Provider	Reference Year	Proxy?
DE	Polypropylene Granulate (PP)	Sphera	2018	Geo.
DE	Polyethylene low density granulate (LDPE/PE-LD)	Sphera	2020	Geo.
EU-28	Methanol mix	Sphera	2020	No
EU-28	Methanol from natural gas (combined reforming)	Sphera	2020	No
EU-28	Nitrogen (gaseous)	Sphera	2020	No
EU-28	Naphtha at refinery	Sphera	2017	No
EU-28	Natural gas mix	Sphera	2017	No
EU-28	Hydrogen (steam reforming natural gas)	Sphera	2020	No
EU-28	Sodium hydroxide mix (50%)	Sphera	2020	No
EU-28	Sodium hydroxide (caustic soda) mix (100%)	Sphera	2020	No
EU-28	Sulphuric acid (96%)	Sphera	2020	No
DE	Urea (stamicarbon process)	Sphera	2020	Geo.
GLO	Compressed air 7 bar (low power consumption)	Sphera	2020	No
GLO	Catalyst	Sphera	2020	No
EU-28	Hydrogen (Europipeline)	Sphera	2020	No
EU-28	Water (deionised)	Sphera	2020	No
EU-28	Water (desalinated; deionised)	Sphera	2020	No
EU-28	Process water from surface water	Sphera	2020	No
DE	Waste incineration (plastics)	Sphera	2020	Geo.
EU-28	Commercial waste in municipal waste incineration plant	Sphera	2020	No
GLO	Plastic Film (PE, PP, PVC)	Sphera	2020	No
EU-28	Polyethylene (PE) in waste incineration plant	Sphera	2020	No
EU-28	Polypropylene (PP) in waste incineration plant	Sphera	2020	No
EU-28	Plastic packaging in municipal waste incineration plant	Sphera	2020	No
EU-28	Municipal waste in waste incineration plant	Sphera	2020	No
EU-28	Municipal wastewater treatment (mix)	Sphera	2020	No
EU-28	Municipal solid waste on landfill	Sphera	2020	No
EU-28	Plastic waste on landfill	Sphera	2020	No
EU-28	Hazardous waste (statistical average) (C rich, worst case scenario incl. landfill)	Sphera	2020	No
GLO	Hazardous waste (non-specific) (C rich, worst case scenario incl. landfill)	Sphera	2020	Geo.
EU-28	Municipal household waste (AT, DE, IT, LU, NL, SE, CH) on landfill	Sphera	2020	No

*Proxy legend: Geo = Geographical, Tech = Technology, Temp = Temporal

3.4.3. Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials for production and assembly facilities. The GaBi 2021 transportation database was used to model transportation. Fuels were modelled using the geographically appropriate datasets.

Table 3-27: Transportation and road fuel datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Truck	GLO	Bulk waste truck, Euro 5, 20 - 26t gross weight / 10t payload capacity (urban area)	Sphera	2020	Geo.
	GLO	Bulk waste truck, Euro 5, 20 - 26t gross weight / 10t payload capacity (rural area)	Sphera	2020	Geo.
	GLO	Bulk waste truck, Euro 6, 20 - 26t gross weight / 10t payload capacity (rural area)	Sphera	2020	Geo.
	GLO	Bulk waste truck, Euro 6, 20 - 26t gross weight / 10t payload capacity (urban area)	Sphera	2020	Geo.
Diesel	EU-28	Diesel mix at filling station	Sphera	2017	No
Pipeline	GLO	Product pipeline		2020	Geo.

*Proxy legend: Geo = Geographical, Tech = Technology, Temp = Temporal

3.5. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment to provide a transparent link between the inventory and impact assessment results.

Table 3-28: Selected LCI results of the product systems assessed (in kg)[14][15]

Flows	A.1	B.1	A.2	B.2	A.3	B.3	A.4	B.4	A.5	B.5	A.6	B.6
Feedstock	CR Pyrolysis oil	Virgin fossil naphtha	CR Pyrolysis oil-better yield	Virgin fossil naphtha	CR Pyrolysis oil	Virgin fossil naphtha	CR Pyrolysis oil-better yield	Virgin fossil naphtha	CR Pyrolysis oil	Virgin fossil naphtha	CR Pyrolysis oil	Virgin fossil naphtha
EoL	CR	100% Incineration	CR	100% Incineration	CR	100% Incineration	CR	100% Incineration	CR	100% Landfill	CR	55 % Landfill, 45 % incineration
Electricity grid mix	Current	Current	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030
Resources												
Crude oil (in MJ)	-401.2	1114.1	-429.4	1114.3	-405.5	1122.4	-433.7	1122.3	-403.1	1148	-404.2	1136.4
Hard coal (in MJ)	65.3	-100.5	64.7	-97.2	54.9	-80.6	54.4	-78	67.1	66.1	61.6	0.1
Lignite (in MJ)	126.9	-192.2	125.8	-186.2	87.6	-117.3	86.8	-113.6	107.2	104.6	98.4	4.7
Natural gas (in MJ)	371.2	-223.4	368.6	-208	365.5	-212.5	362.9	-197.5	431.4	565.2	401.7	215.2
Water	2351250	-3858191	2330010	-3734041	2767900	-4651836	2743498	-4503739	3401702	3108560	3116491	-383618
Air	32218	37549.2	31770.3	37145.7	31761.8	38418.2	31317.6	37988.5	29248.3	13925.7	30379.3	24947.3
Carbon dioxide	508.2	-187.9	502.4	-181.9	528.8	-226.9	522.8	-219.8	560.4	156.6	546.1	-16
Nitrogen	3.21E+01	-1.45E-08	3.11E+01	-1.41E-08	3.21E+01	-1.81E-08	3.11E+01	-1.75E-08	3.21E+01	1.18E-08	3.21E+01	-1.66E-09
Oxygen	506.3	-0.2	491.9	-0.1	506.3	-0.1	491.8	-0.1	506.3	0.2	506.3	0
Emissions to air												
Ammonia	0.085	0.098	0.083	0.097	0.087	0.094	0.086	0.093	0.079	0.028	0.083	0.058
Carbon dioxide	2953.7	5244.9	2886.6	5179	2842.4	5457	2776.1	5384.7	2563.6	1967.6	2689	3537.8
Carbon dioxide (biotic)	577.5	-186.9	568.8	-181	597.9	-225.8	589.1	-218.7	591.7	155.1	594.5	-16.3

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[14] Negative values are due to the system expansion approach and credits for material and energy substitutes.

[15] Highest impacts to each category is indicated in red.

Flows	A.1	B.1	A.2	B.2	A.3	B.3	A.4	B.4	A.5	B.5	A.6	B.6
Feedstock	CR Pyrolysis oil	Virgin fossil naphtha	CR Pyrolysis oil-better yield	Virgin fossil naphtha	CR Pyrolysis oil	Virgin fossil naphtha	CR Pyrolysis oil-better yield	Virgin fossil naphtha	CR Pyrolysis oil	Virgin fossil naphtha	CR Pyrolysis oil	Virgin fossil naphtha
EoL	CR	100% Incineration	CR	100% Incineration	CR	100% Incineration	CR	100% Incineration	CR	100% Landfill	CR	55 % Landfill, 45 % incineration
Electricity grid mix	Current	Current	2030	2030	2030	2030	2030	2030	2030	2030	2030	2030
Carbon dioxide (land use change)	1.2	-0.9	1.2	-0.9	1.5	-1.4	1.4	-1.3	1.7	1.5	1.6	0.2
Carbon monoxide	1.4	0.3	1.4	0.3	1.4	0.3	1.4	0.3	1.6	1.5	1.5	0.9
Nitrogen dioxide	7.389E-03	5.647E-03	7.228E-03	5.524E-03	7.545E-03	5.349E-03	7.383E-03	5.236E-03	7.772E-03	7.773E-03	7.670E-03	6.682E-03
Nitrogen monoxide	0.0655	0.0523	0.0641	0.0512	0.0669	0.0496	0.0655	0.0485	0.0687	0.0691	0.0679	0.0603
Nitrogen oxides	3.15	0.39	3.10	0.44	3.01	0.65	2.96	0.69	3.18	2.90	3.11	1.89
Sulphur dioxide	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.4	0.5	1.8	0.5	1.2
NMVOC (unspecified)	0.68	1.13	0.67	1.13	0.68	1.13	0.67	1.13	0.69	1.20	0.69	1.17
Methane	0.6	3.2	0.5	3.3	0.5	3.4	0.4	3.5	1	8.1	0.8	6
Methane (biotic)	1.73	-0.1	1.67	-0.09	1.7	-0.05	1.65	-0.05	3.97	0.31	2.95	0.15
Emissions to fresh water												
Nitrogen dioxide	3.87E-04	-2.77E-04	3.86E-04	-2.61E-04	3.83E-04	-2.67E-04	3.81E-04	-2.52E-04	4.48E-04	5.05E-04	4.18E-04	1.57E-04
Phosphorus	3.01E-03	2.50E-04	2.94E-03	2.60E-04	3.08E-03	1.24E-04	3.01E-03	1.38E-04	6.41E-03	2.54E-02	4.91E-03	1.40E-02
Sulphide	-0.097	0.271	-0.104	0.271	-0.098	0.273	-0.105	0.273	-0.097	0.284	-0.098	0.279
Emissions to sea water												
Nitrogen	1.56E-07	-1.11E-07	1.56E-07	-1.05E-07	1.54E-07	-1.08E-07	1.54E-07	-1.02E-07	1.81E-07	2.03E-07	1.69E-07	6.30E-08
Phosphorus	1.24E-07	-2.03E-07	1.23E-07	-1.96E-07	3.10E-08	-2.58E-08	3.07E-08	-2.46E-08	3.66E-08	4.21E-08	3.41E-08	1.15E-08
Sulphide	-2.65E-02	7.36E-02	-2.84E-02	7.36E-02	-2.69E-02	7.43E-02	-2.87E-02	7.43E-02	-2.67E-02	7.60E-02	-2.68E-02	7.52E-02

7

4. LCIA Results

This chapter contains the results for the impact categories climate change and fossil resource use defined in section 2.7.

It shall be reiterated that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would follow the underlying impact pathway. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1. Overall Results

Climate change

Figure 4-1 shows the overall climate change results for the scenarios assessed including the process contribution to the totals. The EoL burdens are shown separately from EoL credits. The EoL credits show negative values due to material and energy substitutes during waste treatment. The EoL credits of the Py-CR product systems cover naphtha for material substitutes. The EoL credits of the conventional product systems include electricity grid mix substitutes and thermal energy substitutes from natural gas. Given that the production of pyrolysis oil fulfils two functions, system expansion was applied for the comparative scenarios to account for the equivalent burdens and credits of waste managed during production. This includes the waste collection, sorting, and waste treatment according to the EoL option assessed in each scenario.

The overall climate change results of the Py-CR product systems are lower (2859 to 3048 kg CO_2 eq.) than the primary naphtha production (5292 to 5576 kg CO_2 eq.) with EoL incineration (scenarios 1-4). As compared to the current incineration option, the current Py-CR product system shows 43% GWP reduction (scenario 1) and 44% reduction in scenario 2 given a 5% higher yield for Py-CR. The degree of GWP reduction is even higher (47%) when this scenario is assessed for future electricity grid mix (for 2030 in scenario 3) and 48% when the future electricity grid mix and a 5% higher yield were combined (scenario 4).

The total GWP of the Py-CR product system (2748 kg CO_2 eq.) is 20% higher than the primary naphtha product system with landfill accounting for 2292 kg CO_2 eq. (scenario 5).

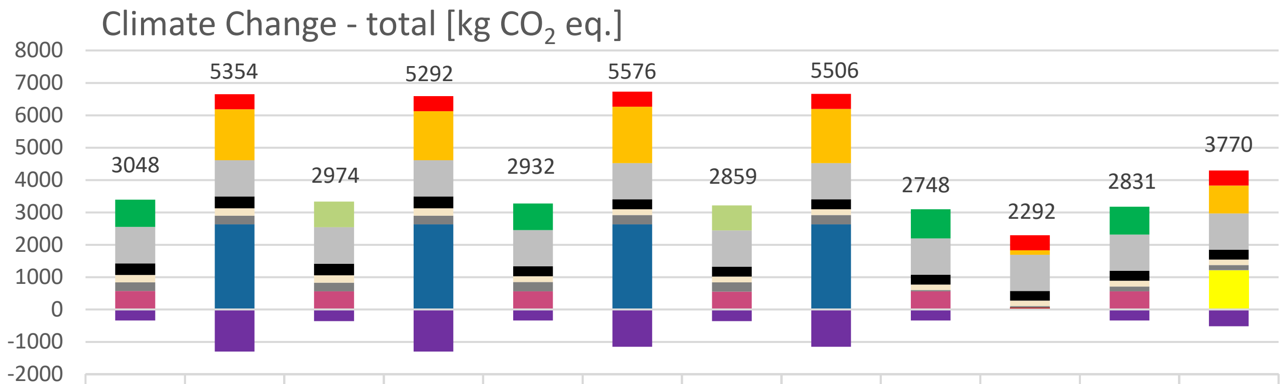
The total GWP of the Py-CR product system (2831 kg CO_2 eq.) is 25% lower compared than the primary naphtha product system with a mixed EoL treatment (55% landfill and 45% incineration) accounting for 3770 kg CO_2 eq. (scenario 6).

Overall, the results show that the Py-CR pathway has lower total GWP than the primary naphtha production with 100% incineration and mixed EoL (55% landfill and 45% recycling), but higher GWP than the 100% landfill scenario. The product systems with EoL incineration and mixed EoL are mainly driven by combustion emissions during waste incineration resulting in higher total GWP results compared to the Py-CR product systems. Due to the waste incineration impacts, the Py-CR product systems also perform better, if credits for EoL materials and energy recovery would be disregarded in case of a cut-off approach.

The difference of a higher yield (5%) for the Py-CR process (scenario 2) results in a slightly lower impact of 1% compared to the current Py-CR product system and incineration-based product system (scenario 1). The higher yield reduces the impact of the Py-CR process as well as the amount to be considered for system expansion for the incineration-based product system.

The GWP results for the primary naphtha production with EoL landfilling (60 kg CO_2 eq.) is comparatively low due to lower waste treatment process emissions compared to other waste treatment options.

The potential climate change impacts are driven by inorganic emissions to air, primarily carbon dioxide. The contribution analysis shows that the highest impacts to overall GWP results of the comparative systems are caused by carbon dioxide emissions during waste incineration, followed by combustion emissions during steam cracking. For the Py-CR product system, the highest contributions to total GWP results occur during steam cracking and associated combustion emissions. This is followed by combustion emissions caused by process gas to produce heat in the Py-CR process.



	A.1	B.1	A.2	B.2	A.3	B.3	A.4	B.4	A.5	B.5	A.6	B.6
	Current electricity mix				2030 electricity mix							
🟩 Pyrolysis oil	841				823				897		864	
🟩 Pyrolysis oil, 5% higher yield			792				775					
🟥 Naphtha		465		465		465		465		465		465
🟧 System expansion (waste collection, sorting, EoL treatment)		1577		1514		1745		1676		133		858
⬜ Steam cracking	1124	1124	1124	1124	1120	1120	1120	1120	1120	1120	1120	1120
⬛ Polymerisation	364	364	364	364	304	304	304	304	304	304	304	304
⬜ Film Extrusion	222	222	222	222	178	178	178	178	170	170	173	173
◼ EoL Waste collection & sorting	270	270	270	270	290	290	290	290	41	41	153	153
🟥 EoL chemical recycling	570		559		560		549		560		560	
🟦 EoL incineration		2631		2631		2631		2631				
🟥 EoL landfill										60		
🟨 EoL landfill & incineration												1217
🟪 EoL Credits (material and energy substitutes)	-343	-1298	-357	-1298	-343	-1157	-357	-1157	-343	0	-343	-521
Total	3048	5354	2974	5292	2932	5576	2859	5506	2748	2292	2831	3770
Reduction / Increase of CR scenario over benchmark	-43%		-44%		-47%		-48%		+20%		-25%	

Figure 4-1: Global warming potential per tonne of PE/PP food grade film and 1.26 tonne of mixed plastic waste managed

Fossil resource use

Figure 4-2 shows the fossil resource use results for the assessed scenarios with the process contributions. It should be noted that the system expansion and waste collection and sorting processes show aggregated, negative values due to associated credits for material and energy substitutes outweighing burdens, while EoL burdens and EoL credits are shown separately for each EoL option.

The results show that the total fossil resource use from the Py-CR pathway (3513 to 8977 MJ) is 76-89% lower than all comparative product systems (25935 to 79762 MJ).

The total fossil resource use results of pyrolysis oil are lower (3513 to 6277 MJ) compared to the fossil naphtha product systems (25935 to 29584 MJ) with incineration at the end-of-life (scenarios 1-4). As compared to the current incineration option, the current Py-CR product system has a 76% lower total fossil resource consumption (scenario 1) and an 82% lower with a 5% higher Py-CR yield (scenario 2) option. The potential reduction in fossil resource use increases up to 83% for the Py-CR option when the future electricity grid mix 2030 was used (scenario 3) and to 88% with a future electricity grid mix plus 5% higher yield (scenario 4).

The total fossil resource consumption of the Py-CR product system (8977 MJ) is 89% lower compared to the product system with landfill (scenario 5). Compared with the mixed EoL treatment scenario, the total fossil resource use of the Py-CR product is (7235 MJ) 87% lower (scenario 6).

Among all product systems, the fossil resource use is highest for the primary naphtha production with EoL landfill (79762 MJ) as this product system does not benefit from any credits for material /energy substitutes.

The contribution analysis shows that the highest impact of the comparative systems is caused by the naphtha production from crude oil as the main driver. As the fossil content of the raw material for Py-CR process is sourced from mixed plastic waste which is burden-free based on the value correction substitution approach[16], the natural gas consumption during steam cracking is the main contributor to overall fossil resource use for the Py-CR product system.

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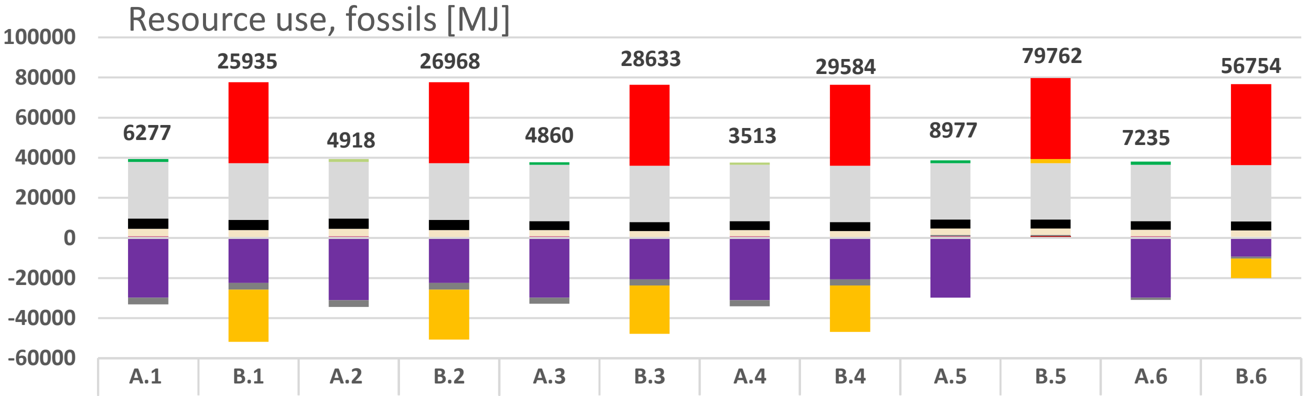
[16] Please see section 2.5.2 for further information of EoL allocation approaches.



	A.1	B.1	A.2	B.2	A.3	B.3	A.4	B.4	A.5	B.5	A.6	B.6
	Current electricity mix				2030 electricity mix							
🟩 Pyrolysis oil	1528				1312				1558		1558	
🟩 Pyrolysis oil, 5% higher yield			1452				1246					
🟥 Naphtha		40467		40467		40467		40467		40467		40467
🟧 System expansion (waste collection, sorting, EoL treatment)		-26026		-24994		-23975		-23024		2040		-9667
⬜ Steam cracking	28145	28145	28145	28145	28096	28096	28096	28096	28096	28096	28096	28096
⬛ Polymerisation	5132	5132	5132	5132	4392	4392	4392	4392	4392	4392	4392	4392
⬜ Film Extrusion	3638	3638	3638	3638	3106	3106	3106	3106	3228	3228	3173	3173
⬛ EoL Waste collection & sorting	-3328	-3328	-3328	-3328	-3088	-3088	-3088	-3088	661	661	-1026	-1026
🟪 EoL chemical recycling	952		941		832		822		832		832	
🟦 EoL incineration		321		321		321		321				
🟥 EoL landfill										877		
🟨 EoL landfill & incineration												627
🟪 EoL Credits (material and energy substitutes)	-29790	-22414	-31062	-22414	-29790	-20687	-31062	-20687	-29790	0	-29790	-9309
Total	6277	25935	4918	26968	4860	28633	3513	29584	8977	79762	7235	56754
Reduction / Increase of CR scenario over benchmark	-76%		-82%		-83%		-88%		-89%		-87%	

Figure 4-2: Fossil resource use per tonne of food grade film and 1.26 tonne of mixed plastic waste managed

4.2. Scenario Analysis

4.2.1. Collection rate

To test the influence of the assumed collection rate of 85% at end-of-life to meet European plastic recycling targets of 55% (European Parliament, 2018), the collection rate was evaluated in a scenario analysis given a collection rate of 30% according to another literature source (Antonopoulos et al., 2021) and 100% to provide an outlook of potential reduction of environmental impacts for Py-CR.

Table 4-1 shows the overall LCIA results for the product systems assessed and the relative deviation compared to the baseline results. Deviations from the baseline of more than ±20% are marked in red.

The scenario analysis shows that the LCIA results with a collection rate of 30% and 100% show higher changes of results for the Py-CR product systems than the comparative systems. The lower collection rate of 30% for the Py-CR product systems is due to higher amounts of rejected waste for the Py-CR processing being managed according to the EoL options considered. The changes of managed and rejected quantities for the conventional EoL options are marginal.

Regarding the climate change results, with a collection of 30%, deviations greater than 20% occur for the Py-CR product systems compared to the incineration scenarios (scenario 1-4), while changes in impact results for the incineration scenarios are not relevant (Figure 4-3). However, these deviations do not change the ranking of results between Py-CR and the incineration-based product systems. Given a collection of 100%, changes in the total climate change results remain below 20% for all product systems assessed.

For fossil resource consumption, deviations greater than 20% occur for the Py-CR systems for both collection rates (30% and 100%) in all scenarios, while changes in impact results for the comparator systems are not relevant (Figure 4-4). However, these deviations do not change the ranking between Py-CR and the comparative systems assessed.

Table 4-1: LCIA results for products systems assessed with different collection rates of 85% (base case), 30%, and 100% (scenarios)

Product systems	GWP, total [kg CO_2 eq.]	GWP, total [%] Deviation	Resource use, fossils [MJ]	Resource use, fossils [%] Deviation
A.1 CR Pyrolysis oil, pyrolysis, current electricity mix, 85% collection rate	3048		6277	
A.1 CR Pyrolysis oil, pyrolysis, current electricity mix, 30% collection rate	3748	+23%	10375	+65%
A.1 CR Pyrolysis oil, pyrolysis, current electricity mix, 100% collection rate	2857	-6%	5159	-18%
B.1 Naphtha, 100% Incineration, current electricity mix, 85% collection rate	5354		25935	
B.1 Naphtha, 100% Incineration, current electricity mix, 30% collection rate	5339	0%	25668	-1%
B.1 Naphtha, 100% Incineration, current electricity mix, 100% collection rate	5358	0%	26008	0%
A.2 CR Pyrolysis oil, higher yield, pyrolysis, current electricity mix, 85% collection rate	2974		4918	
A.2 CR Pyrolysis oil, higher yield, pyrolysis, current electricity mix, 30% collection rate	3690	+24%	9846	+100%
A.2 CR Pyrolysis oil, higher yield, pyrolysis, current electricity mix, 100% collection rate	2779	-7%	3574	-27%
B.2 Naphtha, 100% Incineration, current electricity mix, 85% collection rate	5292		26968	
B.2 Naphtha, 100% Incineration, current electricity mix, 30% collection rate	5277	0%	26701	-1%
B.2 Naphtha, 100% Incineration, current electricity mix, 100% collection rate	5296	0%	27041	0%
A.3 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 85% collection rate	2932		4860	
A.3 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 30% collection rate	3733	+27%	10195	+110%
A.3 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 100% collection rate	2713	-7%	3406	-30%
B.3 Naphtha, 100% Incineration, 2030 electricity mix, 85% collection rate	5576		28633	
B.3 Naphtha, 100% Incineration, 2030 electricity mix, 30% collection rate	5564	0%	28408	-1%
B.3 Naphtha, 100% Incineration, 2030 electricity mix, 100% collection rate	5579	0%	28694	0%
A.4 CR Pyrolysis oil, higher yield, pyrolysis, 2030 electricity mix, 85% collection rate	2859		3513	
A.4 CR Pyrolysis oil, higher yield, pyrolysis, 2030 electricity mix, 30% collection rate	3676	+29%	9677	+175%
A.4 CR Pyrolysis oil, higher yield, pyrolysis, 2030 electricity mix, 100% collection rate	2636	-8%	1832	-48%
B.4 Naphtha, 100% Incineration, 2030 electricity mix, 85% collection rate	5507		29584	
B.4 Naphtha, 100% Incineration, 2030 electricity mix, 30% collection rate	5495	0%	29359	-1%
B.4 Naphtha, 100% Incineration, 2030 electricity mix, 100% collection rate	5510	0%	29645	0%
A.5 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 85% collection rate	2748		9178	

Product systems	GWP, total [kg CO_2 eq.]	GWP, total [%] Deviation	Resource use, fossils [MJ]	Resource use, fossils [%] Deviation
A.5 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 30% collection rate	2635	-4%	28258	+208%
A.5 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 100% collection rate	2779	1%	3974	-57%
B.5 Naphtha, 100% landfill, 2030 electricity mix, 85% collection rate	2292		79762	
B.5 Naphtha, 100% landfill, 2030 electricity mix, 30% collection rate	2280	-1%	79537	0%
B.5 Naphtha, 100% landfill, 2030 electricity mix,100% collection rate	2295	0%	79537	0%
A.6 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 85% collection rate	2831		7235	
A.6 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 30% collection rate	3129	11%	20130	+178%
A.6 CR Pyrolysis oil, pyrolysis, 2030 electricity mix, 100% collection rate	2749	-3%	3718	-49%
B.6 Naphtha, 55% landfill, 45% incineration, 2030 electricity mix, 85% collection rate	3770		56754	
B.6 Naphtha, 55% landfill, 45% incineration, 2030 electricity mix, 3 0% collection rate	3758	0%	56529	0%
B.6 Naphtha, 55% landfill, 45% incineration, 2030 electricity mix, 100% collection rate	3773	0%	56815	0%

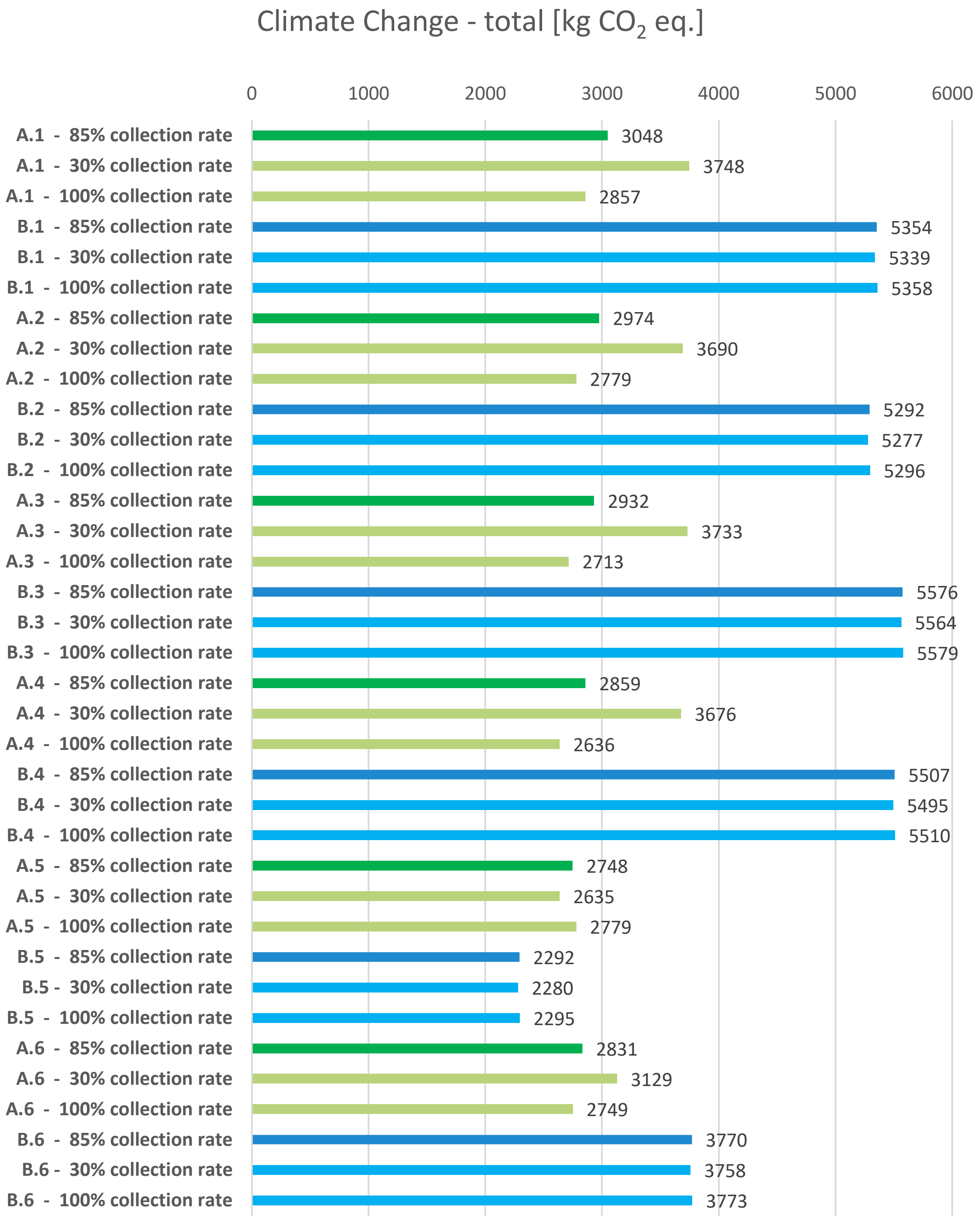


Figure 4-3: Global warming potential per FU with a collection rate of 85%, 30% and 100%

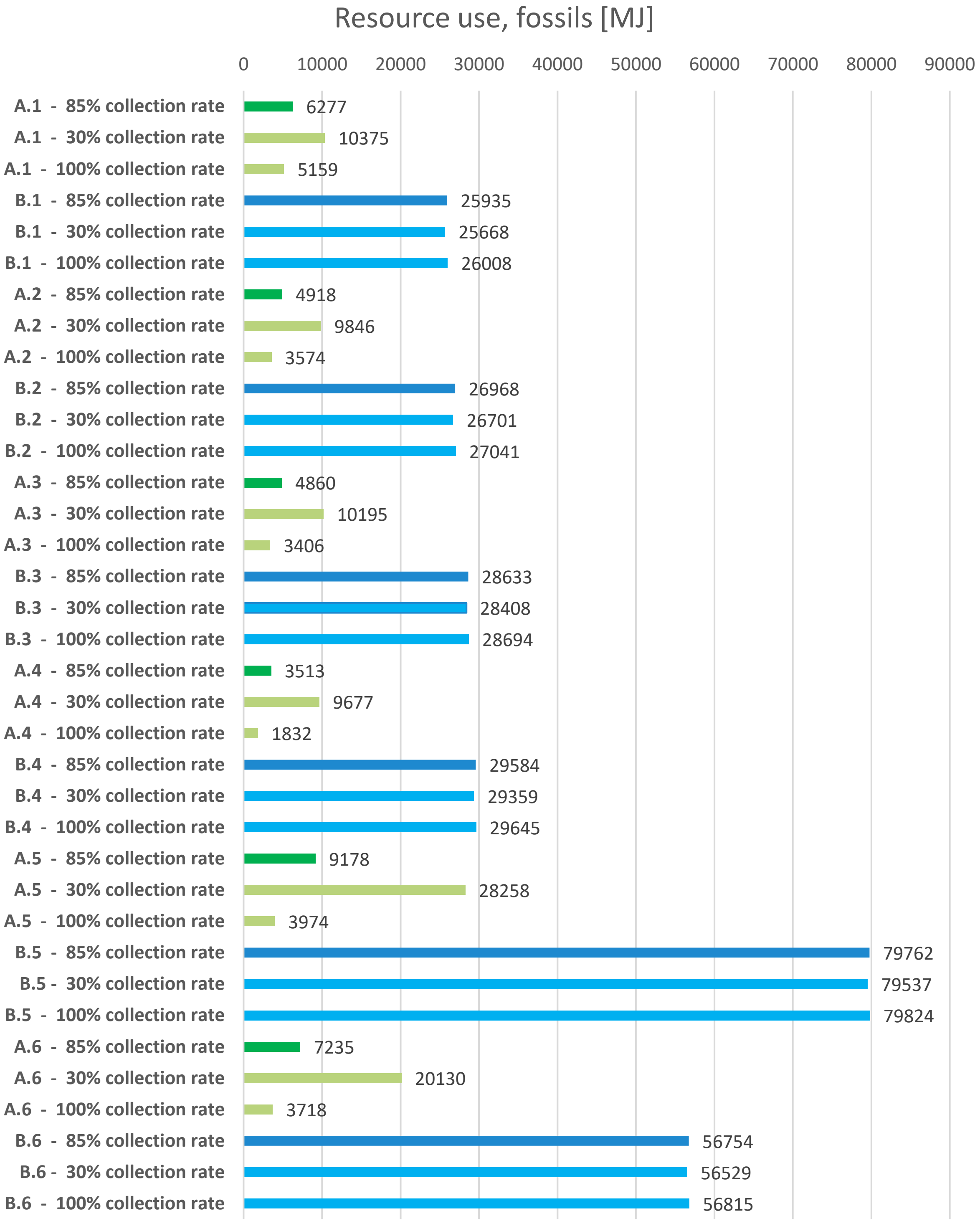


Figure 4-4: Fossil resource use per FU with a collection rate of 85%, 30% and 100%

4.2.2. Electricity credits

To test the influence of energy credit assumptions based on the electricity grid mix in the base scenario, the electricity substitutes were evaluated in a scenario analysis with electricity from coal and natural gas for scenario 1 (A.1 and B.1).

Table 4-2 shows the overall LCIA results for the product systems assessed and the relative deviation compared to the baseline results. Deviations of more than ±20% are marked in red.

The scenario analysis of electricity assumptions shows deviations of life cycle impact results of more than ±20% for the incineration-based product system (-44% to -5%), while the changes of total impacts remain below 20% for the Py-CR product system (-17% to -1%). Deviations of more than ±20% of total LCIA results across all impact categories occur only for the incineration-based product system with electricity credits based on electricity from coal (-44% to -41%).

The electricity credits based on electricity from coal and natural gas has higher amounts of fossil energy sources than in the average electricity grid mix considered in the base case. This leads to a higher impact profile and accordingly higher credits to be accounted for in the incineration-based product systems and lower potential reduction of the Py-CR product system over the benchmark system accordingly.

Compared to the base case, the total life cycle results of both incineration-based product systems assuming coal power and natural gas decrease for all impact categories.

Overall, the relative ranking between Py-CR and the conventional product system with EoL incineration remains the same regardless of which source of electricity is substituted. However, the difference becomes marginal in the following cases: While the total GWP result of the Py-CR product system is relevantly lower (-44%) compared to the conventional incineration-based product system in the base case, the GWP result of Py-CR product system is only 8% lower compared the conventional product system when coal power is assumed.

Table 4-2: LCIA results for the current products systems with electricity credits based on electricity grid mix (base case), electricity from coal and natural gas (scenarios)

Product systems	GWP, total [kg COs eq.]	GWP, total [%] Deviation	Resource use, fossils [MJ]	Resource use, fossils [%] Deviation
A.1 CR Pyrolysis oil, chemical recycling, current electricity mix, credits based on electricity grid mix	3048		6277	
A.1 CR Pyrolysis oil, chemical recycling, current electricity mix, credits based on electricity from coal	2813	-8%	5214	-17%
A.1 CR Pyrolysis oil, chemical recycling, current electricity mix, credits based on electricity from natural gas	3019	-1%	5885	-6%
B.1 Naphtha, 100% Incineration, current electricity mix, credits based on electricity grid mix	5354		25935	
B.1 Naphtha, 100% Incineration, current electricity mix, credits based on based on electricity from coal	3010	-44%	15311	-41%
B.1 Naphtha, 100% Incineration, current electricity mix, credits based on based on electricity from natural gas	5062	-5%	22024	-15%

5. Interpretation

5.1. Identification of Relevant Findings

For the study, the plastic-to-plastic life cycle impacts of food-grade plastic film made from chemically recycled pyrolysis oil were assessed and compared to those of food-grade plastic film made from primary naphtha and different EoL treatment options.

The key findings of the study are as follows:

- Regarding climate change, the Py-CR product system shows lower total GWP results compared to the product systems with EoL incineration and mixed EoL benefitting from lower impacts for waste treatment than incineration. Due to the waste incineration impacts, the Py-CR product systems also performs better when credits for EoL materials and energy recovery are disregarded in case of a cut-off approach. The impacts during feedstock production of pyrolysis oil are higher compared to primary naphtha production; however, the overall GWP results are determined by emissions from incineration at EoL. In addition, the Py-CR product systems still perform better than the incineration-based systems when the burdens and benefits from system expansion due to the additional functionality of Py-CR are not considered.
  The contribution analysis shows that the highest contributions to the overall GWP results of the comparator systems are mainly caused by carbon dioxide emissions during waste incineration, followed by combustion emissions during steam cracking. For the Py-CR product system, the highest contributions to total GWP results occur during steam cracking and associated combustion emissions. This is followed by combustion emissions caused by process gas to produce heat in the Py-CR process.
  The total GWP of the Py-CR product system is higher compared to the product system with landfilling in EoL. Among all EoL options, landfilling benefits from negligible GHG emissions for waste treatment. The 100% landfilling scenario for the naphtha-based product system therefore has the lowest total GWP; however, it is also the worst option regarding fossil resource depletion as neither material nor energy are recovered for substitution.

- Regarding fossil resource use, the Py-CR product system outperforms all conventional product systems assessed due to the (burden-free) mixed plastic waste used as a feedstock for food grade film production. The highest total fossil resource depletion potential occurs for primary naphtha production with landfilling in EoL as neither material nor energy are recovered for substitution, hence demonstrating the impacts of a linear product system based on primary, fossil-based raw material production and waste treatment without any recycling activity.
  The contribution analysis shows that the highest contribution of the comparative systems is caused by the naphtha production from crude oil as the main driver. As the fossil content of the raw material for Py-CR process is sourced from mixed plastic waste which is burden free based on the value corrected substitution approach, the natural gas consumption during steam cracking is the main contributor to overall fossil resource use for the Py-CR product system.

- Higher yields of the Py-CR process result in slightly lower total GWP results for the Py-CR product system. Given a future electricity grid mix based on higher amounts of renewable energy sources results in higher impacts for the incineration-based product systems due to decreased credits for energy recovery and, thus, extends the potential benefit of the Py-CR product system compared to the conventional product system with EoL incineration.

5.2. Assumptions and Limitations

For the study, the potential environmental impacts of the emerging Py-CR technology to produce pyrolysis oil were assessed and compared to mature primary production of naphtha with different end-of-life options. A relevant limitation of the LCIA results are the assumptions made for setting up all product systems to an anticipated situation of energy mixes in 2030 in Europe. However, the validity of the results is supported by various scenario analyses and a conservative approach to evaluate potential future developments. Given the nature of this assessment, the results of the study are valid for this particular study and the assumptions made should be considered for communication of results and conclusions to avoid potential misinterpretation.

The Py-CR technology was assessed using primary data from conventional pyrolysis based on thermal cracking and pyrolysis based on hydrocracking. The reader should keep in mind that due to the very nature of innovation; every technological process is different and applies to the three technology providers used for this study. However, in the case of this study, the technology processes compared share sufficient commonalities for the purpose of this LCA.

The steam cracking process uses pyrolysis oil instead of the conventional feedstock naphtha. The study assumes the same performance of the steam cracker based on the pyrolysis oil feedstock by replacing the naphtha input for pyrolysis oil on a mass basis, assuming the same net calorific value for both pyrolysis and naphtha. In addition, a hydrotreatment step was considered for the pyrolysis oil to meet the requirements of the steam cracker. However, the true emission profile of the steam cracker based on the pyrolysis oil feedstock can differ significantly in reality and thus, the results of the study are valid for the assumptions made.

The current steam cracking technology is based on fossil fuel combustion. Given that further development of steam cracking enables using renewable energy to heat steam cracker furnaces, the results of the steam cracking process can differ significantly in the future. However, the evaluation of this production route is out of the scope of the study and will not affect the comparative results as altered assumptions for the steam cracking would be applied for both steam cracking processes using either naphtha or pyrolysis oil feedstock.

In recent years, the trend of increasing plastic production and consumption has also raised awareness of environmental impacts arising from mismanaged plastic waste, particularly marine litter. As measurements or models accounting for losses to the environment and subsequent releases of plastics to the oceans are lacking, impacts from plastic losses to the environment (i.e., impacts from litter in any ecosystem) are not further quantified, even if the actual amounts of plastic litter are estimated.

Industry-average data are applied for the comparative product systems, whereas industry-average data will be available for Py-CR only in 5-10 years. However, primary data for the Py-CR processes are based on process design data of different pilot plants in Europe to provide an average of the emerging technology. While the comparative product systems represent well established and mature technologies and relevant technological improvement is not very likely for primary naphtha production, potential impacts of the pyrolysis oil might differ with further technology progress or utilities implemented. Since emissions and environmental impacts of developing technologies are very likely to change with the maturity and scale of industrial processes, the results and conclusions are valid for this study for the assumptions made and should be considered respectively.

The comparative product systems and the downstream film production processes are based on industry-average, region-level data derived from the GaBi database or literature for the technologies assessed.

While the data is representative for regional industry average technologies, site-specific and company specific production sites may differ from regional averages due to efficiency rates or utilities applied.

The base case results cover variability of the product systems by assessing averages of different Py-CR plants and higher yields of the Py-CR process. Given that not enough data was available to run a Monte Carlo analysis, an uncertainty analysis for the LCIA results was not conducted to quantify cumulative effects of model imprecision or input uncertainty,

5.3. Results of Scenario Analysis

Scenario analysis was performed to compare results between different sets of assumptions or modelling choices.

5.3.1. Collection rate

The scenario analysis showed that the LCIA results are sensitive to the assumptions of the EoL collection rate resulting in significant result changes for the Py-CR systems, while the changes of total LCIA results of the comparative systems are not significant. Because the Py-CR systems use plastic waste streams as feedstocks, the collection rate affects the performance of Py-CR process and EoL credits for material substitutes, while the comparative product system are not affected by altered collection rate assumptions. However, the relative ranking between the product systems compared remains unchanged.

Given a lower collection rate of 30% compared to base case with 85% of MPW to be collected, the total impacts of the Py-CR product system increase in climate change and fossil resource use. Regarding climate change, a lower collection rate results in higher impacts during waste collection for the Py-CR product system. The increased total fossil resource use of the Py-CR product system compared to the base case is mainly driven by decreased material credits for naphtha substitutes.

Given a higher collection rate of 100% compared to base case with 85% of MPW to be collected, the total fossil resource use results of the Py-CR product system decreased. The decreased total fossil resource use of the Py-CR product system is mainly driven by increased material credits for naphtha substitutes.

5.3.2. Electricity credits

The scenario analysis showed that the LCIA results are sensitive to the assumption of electricity credits resulting in significant result changes for the conventional product system with EoL incineration, while the results of the Py-CR product system do not change significantly.

The electricity credits given for incineration processes are sensitive to the share of fossil energy sources in the grid mix. Assuming electricity credits based on coal and natural gas result in higher amounts of electricity substitutes for the incineration-based product systems compared to the average electricity grid mix considered in the base case and accordingly, lower potential benefits of the Py-CR product system over the benchmark system.

These deviations do not change the ranking between Py-CR and the conventional product system with EoL incineration, however the difference becomes marginal in case of climate change, given that electricity from coal is assumed.

The results of the scenario analysis indicate that potential advantages of the Py-CR product system over the incineration-based system are dependent on the share of fossil energy sources for electricity consumption assumed. A fossil-heavy energy mix increases the credits for energy recovery of the incineration-based product system and may lead to the point where the incineration-based system may even outperform the Py-CR product system.

5.4. Results of Uncertainty Analysis

While no additional uncertainty analysis was performed as part of the study, the original six scenarios investigated in combination with the scenario analysis on the collection rate and electricity credits are assumed to cover the main uncertainties in the foreground system of the study.

5.5. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi 2021 database were used. The LCI datasets from the GaBi 2021 database are widely distributed and used with the GaBi 9 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.5.1. Precision and Completeness

- ✓ **Precision:** The assessment of the Py-CR technology is based on process design data from primary information sources. Variations across different manufacturers were balanced out by using yearly averages, precision is considered to be reasonable. The other processes in the foreground system are based on secondary data from literature and GaBi databases, accuracy is considered to be adequate. All background data are sourced from GaBi databases with the documented precision.
- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from GaBi databases with the documented completeness.

The quantification of methane emissions from natural gas, crude oil, and coal supply chains is still rarely and inconsistently reported. Hmiel et al. (2020) showed the current studies using bottom-up estimates underestimate methane emissions from fossil fuel extraction and use. Emission factors for methane vary considerably, as they depend on many factors at an oil and gas production site. The data quality of methane emission factors may be improved by the combined use of bottom-up and top-down measurements, but only few studies on top-down measurements exist. (Hmiel et al., 2020; Saunois et al., 2020) Measurements of methane emissions may represent snapshots and are subject to large fluctuations. Top-down calculation methods are also not yet fully reliable, although the International Methane Emissions Observatory launched in 2021 will contribute to improved accuracy. Given the underdeveloped state of methane emissions estimates from the natural gas supply chain, we use GaBi default parameters for this sector, acknowledging that this results in an underestimation of emissions linked to oil and gas extraction. Please refer to Annex B: Sphera Statement for further details.

5.5.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases.
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information,

any third party should be able to approximate the results of this study using the same data and modelling approaches.

5.5.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2020. All secondary data come from the GaBi 2021 databases and are representative of the years 2015-2020 and 2030 for the future scenarios. As the study intended to compare the product systems for the reference year 2020 and 2030 for the future scenarios, temporal representativeness is considered to be high.
- ✓ **Geographical:** All primary and secondary data were collected specific to European region under study. Where region-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be high.
- ✓ **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

5.6. Model Completeness and Consistency

5.6.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.6.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimised by exclusively/predominantly using LCI data from the GaBi 2021 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.7. Conclusions

The pyrolysis-based chemical recycling technology (Py-CR) investigated in this study is capable of reducing the amount of mixed plastic waste (MPW) sent to incineration and landfilling and enabling a high-quality recycling of a low-quality waste stream that is otherwise not suitable for mechanical recycling. While these two benefits are fully aligned with the goals of a circular economy, this life cycle assessment study aimed to establish the environmental impact categories of climate change and fossil resource use of the plastic-to-plastic Py-CR product system compared to a more 'linear' way of producing food-grade PE and PP film using a data-driven and science-based approach. In addition, the study was able to highlight specific hotspots and trade-offs associated with each impact category analysed.

To stay up to date and get more accurate scenarios, Py-CR data should be updated as newer data becomes available. The largest need for data collection of the pyrolysis technology and related chemical recycling technologies, upstream and downstream processes include yields, product properties, quality requirements, collection and sorting rates and efficiencies.

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Annex A: Hydrothermal Upgrading

The technological process described below was shared by one company providing primary data for this LCA study.

Molten plastic and supercritical water (SCW) are continuously input at one end of a heated and pressurised reaction process. As this mixture passes through the reactors, the plastic is cracked to a complex mixture of hydrocarbons, similar in composition to crude oil. The SCW acts as a solvent and very effective heat transfer agent which enables homogeneous reaction conditions to be maintained. The transition from plastic to synthetic crude oil takes approximately 30 minutes with the hot oil/water mixture immediately flash distilled, as it exits the reaction tube, to yield a range of hydrocarbon liquids and high calorific value (CV) process gas which is re-used in the boilers to generate SCW.

The SCW environment is a hydrogen ion donor which acts to reduce cross linking at radical sites following the cleaving of carbon-carbon bonds. The water also acts as a solvent for potential contaminants, such as oxygenated hydrocarbons, amines, chlorides, salts and acids, which means that the hydrocarbon product is effectively washed during the production process leading to high quality, stable product.

Annex B: Sphera Statement

Methane emissions from natural gas, crude oil and coal

Methane emissions contribute significantly to the greenhouse effect. In contrast to determining carbon dioxide emissions, which can be often derived directly from the consumption of energy resources and has been included in reporting for decades, the quantification of methane emissions from the supply chains of natural gas, crude oil and coal is still rarely and inconsistently reported.

The advanced quantification of methane emissions is therefore the focus of the assessment of greenhouse gas emissions from the supply of fossil energy carriers. (Hmiel et al., 2020), demonstrate through carbon-14 measurements on preindustrial ice cores that methane emissions from fossil fuel extraction and use are underestimated in current studies that use bottom-up estimates. Combined data from (Hmiel et al., 2020) and (Saunois et al., 2020) show an increase of methane emissions from fossil fuel supply chains and fossil fuel use by 36 Mt CH4/a to 164 Mt CH4/a, or a relative increase of methane emissions by about 28% compared to previous assumptions.

According to the current state of research, it is not yet clear to what extent the supply and use of oil, natural gas and coal causes these methane emissions.

The data quality of methane emission factors may be improved by the combined use of bottom up and top-down measurements. The exact determination of methane emissions requires the use of detailed data of the activities and facilities along the supply chain. The more detailed the data regarding processes with methane emissions and the respective magnitudes, the higher the quality of the emission factors.

Emission factors for methane vary considerably, as they depend on a large number of influencing factors, including:

- Facility design,
- Gas composition,
- Type of production and processing (e.g., combined oil and gas production),
- Age and technical standard of machinery and equipment, and
- Operating conditions, maintenance conditions, and other operational activities.

Based on current research, few studies have been conducted on top-down measurements of methane emissions. Therefore, top-down measurements and calculation methods for methane emissions are not yet harmonized; neither internationally nor between sectors. Further research needs regarding top-down measurements include the handling of accidental releases and the proper scaling of emissions to the functional unit(s) as a yearly average to account for seasonal variations. Based on the current state of research, data from top-down measurements are therefore not yet consistently applicable to LCAs.

Research and sector alignment is therefore needed, for example, on the allocation of methane emissions between oil and gas in combined oil and gas production. Measurements of methane emissions may represent snapshots and are subject to large fluctuations, which is not yet properly documented in existing studies.

Enhanced and consistent bottom up and top-down analyses and methodologies will contribute to an improved quantification of methane emissions. Sphera closely follows the publication of current studies in this subject area, checks the applicability in LCA and adjusts its LCA datasets when methods lead to an improvement in data quality.

Annex C: Critical Review Statement

- Critical Review Statement –

Life Cycle Assessment of Chemical Recycling for Food Grade Film

Commissioned by:	Consumer Goods Forum
Conducted by:	Sphera
Reviewers:	Jennifer Dunn, Northwestern University (Chair of the review panel) Llorenç Milà i Canals, United Nations Environment Programme Simon Hann, Eunomia Research & Consulting Ltd
References:	ISO 14044:2006 – Environmental Management – Life Cycle Assessment – Requirements and Guidelines ISO/TS 14071:2014 — Environmental management — Life cycle assessment — Critical review processes and reviewer competencies:Additional requirements and guidelines to ISO 14044:2006

Scope of the critical review statement: This document reflects the critical review statement of the reviewers in accordance with ISO 14044:2006 section 6.1. The views expressed in this review statement are those of the external experts is in accordance with ISO 14044:2006 section 6.3 and do not necessarily reflect those of the various affiliated organizations. This review statement is only valid for the specific report titled “Life Cycle Assessment of Chemical Recycling for Food Grade Film” dated April 7th, 2022.

Critical review process: The reviewers have been involved in parallel to the development of the study for a total of four expert panel meetings (one at the beginning, one mid-way through the analysis and two at the end). At the end of the study the reviewers have undertaken two detailed review cycles of the report. Comments from the expert panel were aggregated by the expert panel chair and shared with Sphera using a standard Excel spreadsheet based on Annex A of ISO/TS 14071:2014. The overall review was conducted in an equitable and constructive manner. All comments were reviewed by Sphera and addressed; outstanding issues discussed with the reviewers and a resolution was found for each. The review was performed exclusively on the LCA study report. A copy of the final review report containing all written comments and responses has been provided to the reviewers as well as the study commissioner along with this review statement and shall be made available to third parties upon request. No software models wereshared or requested during the review. Additionally, the reviewer did not review the individual data set shared by data providers given the confidentiality of the information. Statistical spread of the data set could not be shared without compromising the confidentiality of the data given only three data set were averaged in this study.

General evaluation: The reviewers are satisfied with the technical and communications aspects of the report which in their view is consistent with the international standard ISO 14044. Results are scientifically and technically valid, the data used are appropriate and reasonable in relation to the goal of the study, and that the interpretations reflect the limitations identified and the goal of the study. The study report is considered sufficiently transparent and consistent.

However, the reviewers note the following concerns that were unable to be resolved within the time period of the study.

1. Petrochemical industry modeling in LCA

To begin, the steam cracker model within GaBi is used in the process modeling that underpins the LCA results. While the reviewers have requested increased transparency regarding the parameters and modeling approach used in GaBi’s steam cracking model, it has not been possible to achieve this transparency. While the reviewers remain uncomfortable that the report does not provide more details on this model, in the interest of completing the report, we have suggested the following statement be added to the report.

Details of GaBi's steam cracker model are considered intellectual property and cannot be published in a publicly accessible report. This document provides as much detail as possible and it is recognized that, given it must exclude many details, the results of this study may not be replicable without access to the GaBi software.

Furthermore, discussion of the steam cracker assumes readers of the report are familiar with standard methods of handling allocation among co-products in the petrochemical industry. The reviewers believe, for example, that Plastics Europe may take a different approach than GaBi and that Plastics Europe data sets are publicly available. It's not possible to know if there are discrepancies between the co-product handling approaches of GaBi and of Plastics Europe. The reviewers would prefer that the report authors provide a better explanation for how the NCV (Net Calorific Value) allocation is used in the model. The explanation that, "Allocation by net calorific value is applied for co-products of the steam cracker", does not provide the reader sufficient insights to replicate the analysis.

2. Methane emissions in background systems

A second concern the reviewers hold is that the critical background system of crude oil and natural gas acquisition for use in the chemical process is not handled with sufficient detail. In particular, the treatment of fugitive methane emissions occurring in oil and gas extraction was not addressed to the reviewers' satisfaction. Accordingly, the reviewers have suggested that the section on these emissions be written as follows based on the references that are cited therein, the International Methane Emissions Observatory (IMEO), and a recent IMEO report.

The quantification of methane emissions from natural gas, crude oil and coal supply chains is still rarely and inconsistently reported. Hmiel et al. (2020) showed the current studies using bottom-up estimates underestimate methane emissions from fossil fuel extraction and use. Emission factors for methane vary considerably, as they depend on many factors at an oil and gas production site. The data quality of me-thane emission factors may be improved by the combined use of bottom-up and top-down measurements, but only few studies on top-down measurements exist (Hmiel et al., 2020; Saunois et al., 2020). Measurements of methane emissions may represent snapshots and are subject to large fluctuations. Top-down calculation methods are also not fully reliable, although the International Methane Emissions Observatory launched in 2021 will contribute to improved accuracy. Given the underdeveloped state of methane emissions estimates from the natural gas supply chain, we use GaBi default parameters for this sector, acknowledging that this results in an underestimation of emissions linked to oil and gas extraction. Please refer to Annex C: Sphera Statement for further details.

3. NOx emissions and other air pollutants

The reviewers would have preferred that metrics beyond GHG emissions, including air pollutant emissions, receive more attention in this report. It was concluded, however, that prior to finalizing air pollutant emission results, it may be worthwhile to revisit how NOx emissions from municipal solid waste may evolve as incinerators may be dedicated to individual types of waste such as plastic waste. The reviewers strongly recommend NOx and other air pollutant emissions be examined in the next phase of analysis such that as pyrolysis technology develops, care is taken to minimize its air pollution effects.

The reviewers sign this review statement as individual experts. The signatures do not imply an endorsement of the study's scope or results by the affiliated organization.

Jennifer Dunn,
Northwestern University
(Chair of the expert panel)

Llorenç Milà i Canals,
United Nations Environment Programme

Simon Hann,
Eunomia Research & Consulting Ltd